Climate Impacts and U.S. Transportation

Technical Input Report for the National Climate Assessment

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DRAFT

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This is a review draft. The views expressed herein do not necessarily represent the views of the USDOT or the United States Government.

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Cover photo: NASA satellite image of U.S. Route 12, Hatteras Island, North Carolina, after being breached by Hurricane Irene, August 2011. Storm surge cut five new channels between the Atlantic Ocean and Pamlico Sound.

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EXECUTIVE SUMMARY

This report is intended as a technical contribution to the National Climate Assessment (NCA), a quadrennial statutory Federal program to report on change impacts on the United States. The NCA is managed by the Global Change Research Program within White House Office of Science and Technology Policy. The National Climate Assessment has simultaneously commissioned new Federal agency assessments of regional climate impacts, including relative sea level rise, as well as assessments of particular sectors, such as transportation, agriculture, and energy. The agency assessments will be technical inputs to the NCA's national assessment.

The technical input reports are based on two IPCC global greenhouse gas emissions scenarios (A2 and B1). The A2 scenario envisions global emissions continuing to rise through 2100, while the B2 scenario envisions global emissions peaking before 2050, and thereafter declining gradually.

Since of the technical input reports are being prepared simultaneously, it has not been possible for this report to rely on the results of the new science assessments being prepared by other agencies. In lieu of these new assessments, this report primarily relies for climate information on published scientific assessments, particularly the previous national assessment, *Global Climate Change Impacts on the United States* (2009) and other Synthesis and Assessment Products of the Global Change Research Program. The new assessments are likely to be quantitatively different from the earlier report in some cases (notably sea level rise) but qualitatively similar. However, this report will be classified as a **draft report** because the underlying scientific assessments are about to be revised. This report will have to be revised to reflect the new scientific information, and then undergo a more formal peer review process before final approval and dissemination as a U.S. Department of Transportation product.

This report primarily focuses on national-scale system-level effects of climate on U.S. transportation systems over the next century. These effects may be conceptualized as:

- **Systemic impacts**. Changes in the U.S. economy and society induced by climate shifts in agriculture, energy and water may be reflected in changes in transportation systems. Specific topics discussed include potential changes in agricultural transportation induced by shifting cultivation patterns, opening of Arctic seaways, higher shipping costs from declining water levels in the Great Lakes, and transportation aspects of declining U.S. greenhouse gas emissions. The report also discusses systemic risks associated with concentrations of key transportation assets, such as petroleum and grain terminals in the Gulf of Mexico.

- **System reliability and capacity impacts**. Climate impacts on system operations and specific infrastructure elements may potentially reduce capacity, reliability, and, in some cases, safety of U. S. transportation systems. However, system operators may adapt to reduce these effects. While all U.S. transportation systems are potentially affected, this report discusses on effects on urban transportation, aviation, ports, and inland waterways.

Direct climate impacts that may affect transportation systems include:

- Warmer average temperatures and greater frequency of very high temperatures nationally will affect infrastructure design and system operations, particularly pavements, rails, and aviation operations.

- Increased precipitation, and increased precipitation intensity may affect safety and potentially increase the incidence of flood events, threatening fixed infrastructure and affecting system operations.

- Increased hurricane intensity threatens coastal infrastructure.

- Relative sea level rise and storm surge, especially when combined with increased precipitation, threaten specific coastal assets, some of national importance.

I. Introduction

Transportation plays a key role in the functioning of the U.S. economy. The development of swift, reliable, and affordable transportation systems has shaped a unified society and economy. American communities and American society at large both accommodate and require personal mobility. In 2009, 138 million people commuted to work, 86 percent of them by private automobile.[1] In 2010, Americans took some 10.2 billion trips on public transportation.[2] Some 677 million passengers boarded commercial aircraft.[3] The U.S. economy is underpinned by an extensive network of freight systems. American agricultural exports from the Midwest depend upon an elaborate rail, barge, and terminal network to receive inputs and deliver commodity products to markets in the United States and around the world. A 40-foot standardized container can be delivered by truck, rail, and ship to or from virtually any populated location in the world. Petroleum is delivered around the world to U.S. terminals by tankers, refined into gasoline, diesel fuel, and other products, and delivered to customers via a network of pipelines, terminals, and tanker trucks. Transportation links manufacturers with raw materials, consumers with goods, and people with their workplaces, families, and communities.

Climate change will affect the transportation system in two fundamental ways:

- **Systemic impacts.** Climate change-induced effects on the pattern of economic activity and human settlements may induce changes in the transportation systems that support this activity. In particular, changes in agriculture, energy, and water will induce changes in transportation systems.

- **Reliability and capacity impacts**. Transportation systems may be exposed to environmental stresses that are outside the envelope within which they were designed to operate. On a national scale, more frequent failure of individual elements will be experienced as a potential decline in the reliability and capacity of the transportation system, which may be offset in many cases by adaptation action.

Prospective reductions in reliability and increased risk to transportation systems as a whole will manifest themselves as a series of specific issues and operational challenges. There have always been environmental impacts on transportation systems: decreased safety in rainy conditions, mechanical failures in hot weather or network disruption due to snow, ice storms, flooding, and physical damage to infrastructure. Under various climate change scenarios, the frequency of environmental effects is generally expected to increase over the next century, while their predictability is expected to diminish. For transportation system operators, this presents a series of long-term challenges:

- **System design.** Due to systemic impacts, existing infrastructure may become functionally obsolete, while new infrastructure may be required.

- **New or replacement infrastructure design**. The design of new infrastructure depends on projections of future weather and hydrology over the life of the proposed facility. Engineers must consider the likelihood of storm flood events, temperature ranges, quantity and frequency of snow and ice loading in their designs. Since infrastructure being designed now will remain in service for decades, improved predictions of future climate would be useful for new infrastructure design.

- **Existing transportation infrastructure.** Existing infrastructure is vulnerable to damage from extreme or unanticipated weather events. Climate impacts can take the form of physical damage to infrastructure from a variety of environmental causes, or in service interruptions induced by unanticipated conditions.

- **Transportation system operations**. System operations may be affected by environmental conditions or interrupted by extreme events, or alternatively, transportation systems may adapt operational patterns to changing environmental conditions. Reliability may be restored through operational changes, additional investments or technological innovation.

Climate change is not the only factor affecting transportation system reliability: the age of existing infrastructure, the balance between infrastructure investment and transportation demand, changes in spatial development patterns, and the quality of maintenance and operations all affect system performance. Viewed in terms of reliability, the cost of climate impacts on transportation turns out to be a highly non-linear function of system congestion. If the effect of more frequent intense storms is to reduce freeway throughput, for instance, the cost of that reduction will be very high for congested freeways running at capacity, but may be minor for uncongested freeways, since delays are incidental. This general phenomenon likely applies to most transportation modes.

However, this argument also suggests that reliability effects can be reduced, though at some cost. Incipient reliability declines can be averted by investing in additional capacity, redundancy, or remediating specific threats.

The second national climate assessment, *Global Climate Change Impacts in the United States*, detailed the effects of climate change on various transportation modes.[4] Sea level rise raises the potential for permanent inundation along coastal areas while increasing the risk of flooding from storm surge, thus affecting coastal roads, airports, tunnels, rail lines, and ports. Increases in extreme heat may cause pavement and track damage, although the decrease in extreme cold will provide some benefits including reduced snow and ice removal costs. An increase in both the frequency and intensity of extreme weather events such as hurricanes threatens the systemic stability of regional transportation networks.[5]

This technical input to the National Climate Assessment (NCA) is both an update to the previous assessment and an exploration of several new areas. The report is divided into six chapters:

- This introduction;
- An overview of U.S. transportation futures;
- Direct effects of climate change on transportation infrastructure and systems;
- System-level effects of climate change on transportation systems;

- Implications for transportation systems of declining greenhouse gas emissions;
- Regional summaries of climate effects on transportation systems.

In this report, a climate *impact* is defined as a physical phenomenon associated with changing climate, such as sea-level rise. The climate impact then produces some climate *effect* on a transportation system, such as a flooded port.

The topics discussed in chapters IV and V conclude with a risk assessment, which discusses the probability that the climate effect being discussed will actually occur under the two alternative National Climate Assessment scenarios, which are generally consistent with the Intergovernmental Panel on Climate Change (IPCC) A2 (high emissions) and B1 (low emissions scenarios. This approach was recommended by the NCA secretariat.[6]

Probability is ranked qualitatively. In this report, probability is defined as the joint probability that the climate impact will occur, *and* that the transportation effect discussed in the text will actually happen. The probability of the climate impact is drawn from a recent published climate impacts report, while the probability that the transportation effect will occur is based on the author's opinion.

The second element is consequence, which is defined as consequences for the transportation sector, also ranked qualitatively. Consequences have been conceived in terms of economic cost where available, or the extent of national-scale physical and operational changes that would be required as a consequence of the particular effect. The probabilities reported are the opinion of the author, based upon an examination of the available evidence, and should not be construed as a scientific or engineering judgment, or necessarily as reflecting the institutional views of the Department of Transportation or the U.S. Government.

The proper method of measuring climate effects is not always obvious, and there are many subtle problems in attempting to do so. A full discussion of these issues is outside the scope of this report, but specific issues will be discussed in the text as they arise. Some of the considerations associated with the risk assessment approach recommended by the NCA include:

- Effects may be locally severe, but not important on a national scale. This report typically attempts to consider national scale effects.

- The economic cost of the effect may be severe if no action is taken, but small in the presence of cost-effective adaptation action. Generally, this report considers climate effects as net of simple and obviously cost-effective adaptation, or alternatively considers the cost of adaptation as the cost of the action.

- Climate effect costs and effects may be distributed across multiple sectors with some sectors receiving net benefits while others absorb net costs. Where this situation occurs, it is noted in the text, and the assessment is made on national benefits and costs.

- Where economic costs can't easily be determined, and the concept of physical effect has been substituted, and noted in the text.

On the other hand, if climate effects on transportation can be broadly conceptualized as a loss of reliability and capacity, then in the first instance, costs can be modeled in terms of the time, safety and economic losses, noting that the magnitude would be acutely sensitive to the presumed pre-existing level of congestion on the system. Alternatively, costs can be measured as the cost of maintaining or optimizing reliability (i.e. the cost of adaptation is the cost of the effect). This approach can be adapted to distributions of possible climate outcomes, if such distributions can be constructed. However, the approach is problematic for low probability, high consequence events, and for low probability scenarios generally.

Chapter III describes direct climate effects on transportation systems, and Chapter VI describes climate effects on transportation systems within NCA geographic regions. These two chapters do not contain explicit risk analyses, as do other chapters. In the case of Chapter III, it was difficult to meaningfully characterize either risks or consequences in the abstract. In the case of Chapter VI, the many individual risks and consequences defied easy characterization.

This report does not consider scenarios other than the NCA recommended scenarios. There are many useful studies that use assumptions that vary from the NCA scenarios. When these studies are cited, the assumptions actually used are noted where possible.

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[1] USDOT, Bureau of Transportation Statistics (2011), *National Transportation Statistics*, Table 1-41. See: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_41.html

[2] American Public Transit Association, *APTA Ridership Report*, Fourth Quarter 2010. http://www.apta.com/resources/statistics/Pages/RidershipArchives.aspx

[3] USDOT, Bureau of Transportation Statistics (2011), *National Transportation Statistics*, Table 1-44. See: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_41.html

[4] Global Change Research Program (2009), *Global Climate Change Impacts in the United States*, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.). Cambridge University Press, 2009. http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/download-the-report

[5] USGCRP (2009). *Global Climate Change Impacts in the United States*, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson,(eds.). Cambridge University Press, 2009, p. 70. http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf

[6] Moss, R.H., and G. Yohe, 2011: Assessing and Communicating Confidence Levels and Uncertainties in the Main Conclusions of the NCA 2013 Report: Guidance for Authors and Contributors. National Climate Assessment Development and Advisory Committee (NCADAC). See: http://www.globalchange.gov/images/NCA/Draft-Uncertainty-Guidance_2011-11-9.pdf

II. The Transportation Future

A. **Overview**

Transportation sector services account for about 3-10 percent of GNP, but American economy and society are built around the ubiquitous availability of high-quality transportation services.[7] Exports share of GNP peaked in 2008, but remains more than double the 1960 share, while import's share is more three times larger than in 1960.[8]

The U.S. transportation system will continue to increase in scale and complexity along with the U.S. population and economy. Recent decades have also seen international trade playing an expanding role in the U.S. economy. Future climate change impacts will be felt on an expanded transportation system that includes new infrastructure and new technology.

The National Climate Assessment (NCA) will evaluate climate change impacts on the United States in the context of two alternative global greenhouse gas emissions scenarios, originally developed by the Intergovernmental Panel on Climate Change (IPCC).[9] The scenarios chosen are A2, which describes a world with rapidly growing global emissions; and B1, which describes a more community-centric world in which greenhouse gas emissions peak in the near-term, and then begin to decline.

The IPCC A2 and B1 emissions scenarios are both consistent with an expanding global population and economy. There are, however, many possible future paths for the American economy and society that would be consistent with these two global scenarios, as well as many intermediate global emission paths that run between them. In 2007, the U.S. Climate Change Science Program commissioned a socioeconomic modeling exercise, using three different integrated assessment models, which generated projections of U.S. population economic growth over the next 100 years as inputs to an assessment of various emissions scenarios.[10] The results of this integrated assessment are presented in the following sections along with other relevant projections. While the various projections, drawn from multiple sources, are not necessarily consistent with one another, each illustrates a relevant aspect of the social and economic forces that will shape the transportation future.

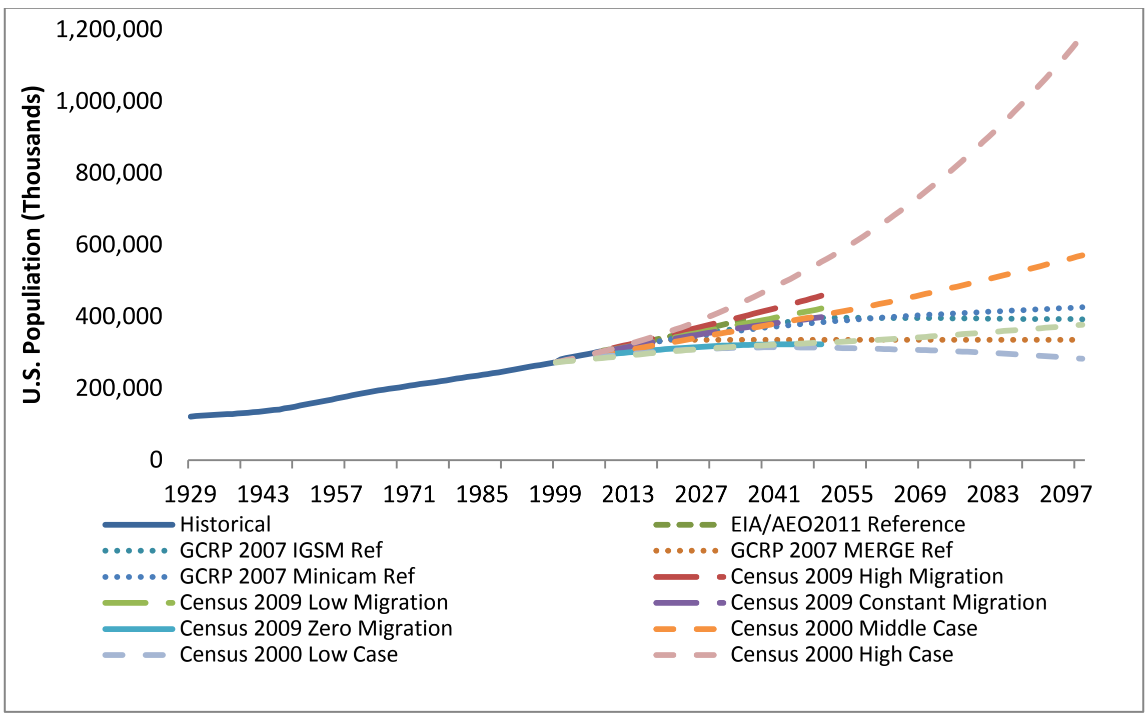
B. **Population**

In addition to the CCSP, the Census Bureau makes regular fifty-year projections of U.S. population and 100-year projections in the wake of each decennial census. Various Federal agencies make (or use) long-term projection of U.S. economic growth, though hundred-year projections are rare. Both the Energy Information Administration and the Department of Transportation's Federal Aviation Administration and the Federal Highways Administration use commercial projections of GDP, population, and other macroeconomic variables as inputs for projections of energy consumption, freight movements, and aviation trends.

While the range of possible futures and their relative probability remain unknown, it is possible to identify a general consensus of demographers and economists about the most likely paths of future population and economic growth in the United States that are broadly consistent with historical experience.

The mid-2010 current estimated population of the United States was 309 million people.[11] The Census Bureau's baseline 2008 projection is for the population of the United States to reach 439 million people by 2050.[12] A subsequent sensitivity analysis, conducted in 2009, to consider the possible effects of international migration, gave a U.S. population range in 2050 from 322 million (assuming zero net international migration) to 458 million (assuming 'high' international migration). [13] Outcomes outside this range are also entirely possible. In 2000, the Census made a set of four projections of population in 2100, based on a range of assumptions about future U.S. fertility, life expectancy, and net international migration. Their 2100 range included an actual decline in population for the low case (282 million), ranging to large increase (1.2 billion people, almost four times the current population) for the highest case.[14] Interestingly, population trends since 2000 are most consistent with the 1.2 billion "high international migration" projection from the 2000 long-term projection (See Figure 1).

Figure 1. U.S. Resident Population, 1929-2011, with Projections to 2100



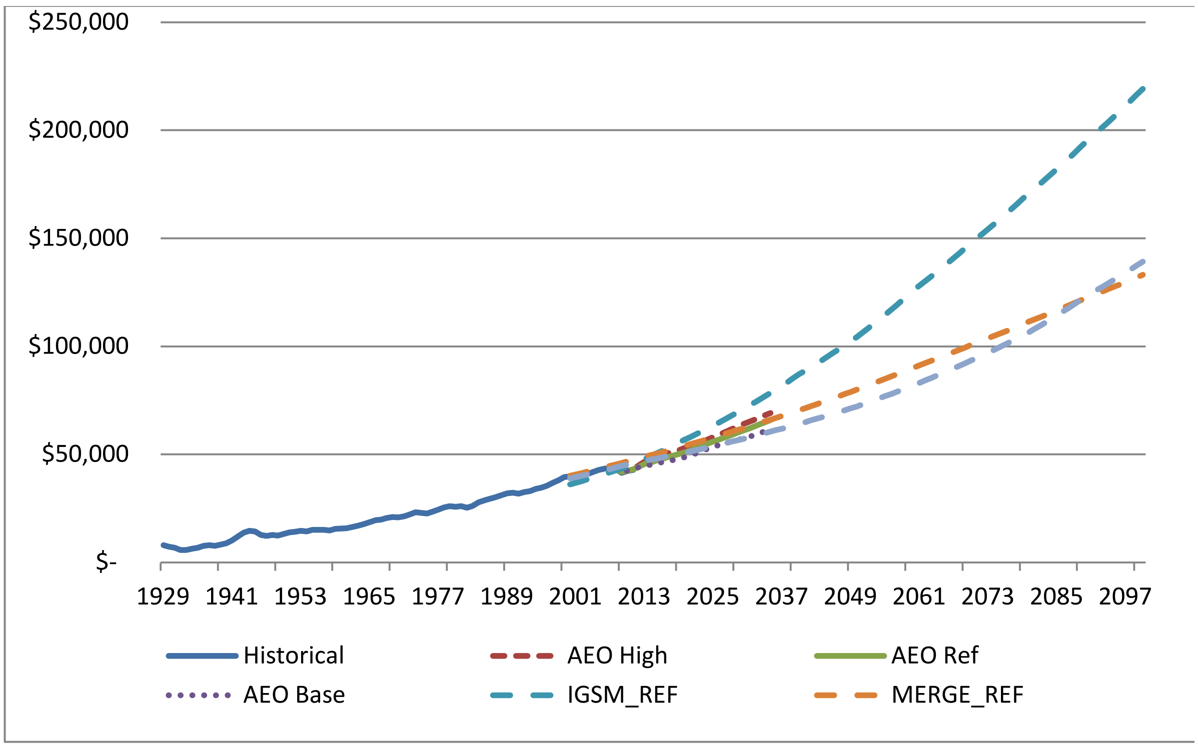
Sources: US Bureau of the Census, US Department of Energy/EIA, *Annual Energy Outlook 2011*, CCSP, 2007: *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B).*

The baseline projection indicates that the fraction of the U.S. population that is over 65 will increase from 13 percent in 2010 to 20 percent in 2050.[15] While the over-65 population in 2050 is likely to be healthier than it is today, the United States is still likely to have a large and growing population of older people in future decades.

C. **Economy**

Along with a rising long-term population, it would be reasonable to expect rising long-term growth in real per capita income. Figure 2 shows Climate Change Science Program's (CCSP) 2007 long-term reference case projections for U.S. per capita Gross Domestic Product, together projections through 2035 undertaken by the Department of Energy's Energy Information Administration (EIA).

Figure 2. U.S. GDP per Capita, 1929-2011, with Projections through 2100



Source: US Department of Energy/EIA, *Annual Energy Outlook 2011*, CCSP, 2007: *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B).* The "IGSM" and "MERGE" data is drawn from the spreadsheet accompanying this report.

During the eighty years between 1929 and 2009, U.S. real per capita GDP increased five-fold. In the EIA modeling, per capita income rises about 50 percent over the next thirty years. The ninety-year projections in the CCSP modeling exercises show per capita income rising between three-fold and five-fold.

A viewer of Figure 1 and Figure 2 might conclude that, given the greater dispersion of population results, that population projections are more uncertain than national income projections. This is incorrect. The small range of GDP estimates is an artifact of the small number of quantified long-term economic projections presented.

D. **Land Use Patterns**

One of the key avenues by which climate change will interact with society and the economy is through changing land use patterns. The Census Bureau's projections, historical evidence, and current trends all argue that the population of the United States will probably continue to grow through the 21st century. If U.S. population continues to grow and current settlement patterns remain unchanged, the area of land devoted to urban and suburban development will increase. A recent study by the Environmental Protection Agency (EPA) attempted to quantify the land use effects of current trends, using two scenarios linked to four IPCC global emissions scenarios, including A2 and B1.[16] The population estimates used in this study was modified from the Census Bureau projections discussed above. For the A2 scenario, the study assumed a U.S. population of about 400 million in 2050 and 700 million in 2100. For the B1 scenario, the study assumed that the U.S. population nearly stabilized at about 350 million in 2050. The Base Case was about 450 million. For the B1 scenario, EPA further assumed a slightly greater disutility of travel time, creating a slight social preference for greater housing density in the B1 scenario compared with A2 and the baseline scenario. While the model included a weather term to model the relative attractiveness of land parcels, the study did not incorporate projected climate-induced temperature change. Table 1 shows the projected increase in urban and suburban land use:

Table 1. Projections of Increases in U.S. Urban & Suburban Land Use, 2000-2100 (Square Kilometers)

Scenario	2000	2050	2100	% Increase, 2000-2100
A2 (High Emissions)	118,468	192,878	312,426	164%
Base Case	118,468	177,066	263,315	125%
B1 (Low Emissions)	118,468	174,063	189,649	60%

Source: U. S. Environmental Protection Agency (EPA). (2009). *Land-Use Scenarios: National-Scale Housing-Density Scenarios Consistent with Climate Change Storylines*. Global Change Research Program, National Center for Environmental Assessment, Washington, DC. EPA/600-R-08/076F, p. 5-9. See: http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203458#Download

There are multiple caveats associated with this work. There are many possible U.S. futures consistent with the global IPCC scenarios, and there are other possible futures inconsistent with the IPCC scenarios. This work assumes that the forces shaping U.S. land use patterns in the future will be broadly similar to those at work in the present. However, the broad implications of the study seem entirely reasonable: a significantly larger U.S. population will cause significant land use conversion to urban and suburban uses, at the expense of other forms of land use. The results also have implications for the transportation sector:

- Increasing urban and suburban populations will require new transportation infrastructure, and absent significant increases in population density, technological change, or transit investment will tend to rely heavily on personal automobiles.

- New infrastructure on new land will be a significant fraction of State and Local infrastructure in 2100. Planning and design decisions for new infrastructure will have a large cumulative effect on the shape of future transportation systems.

- Increasing urban land use will increase storm water run-off for a given level of precipitation, which will increase potential flood risk unless offset by improved storm water management.

Figure 3 illustrates the spatial pattern of the urban and suburban land use projected by the study.

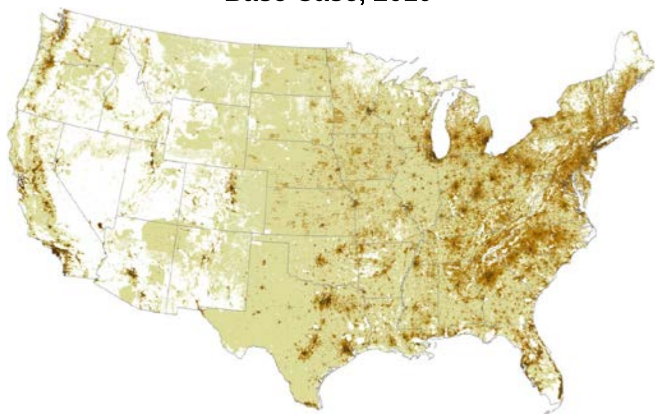
E. **International Trade**

The growing population and economy will spur the demand for transportation services. In the United States, one family of economic projections suggest that the real value of merchandise exports will increase nearly seven-fold, reaching some 27 percent of GDP, while imports will increase four-fold, reaching 22 percent of GDP (Figure 4).

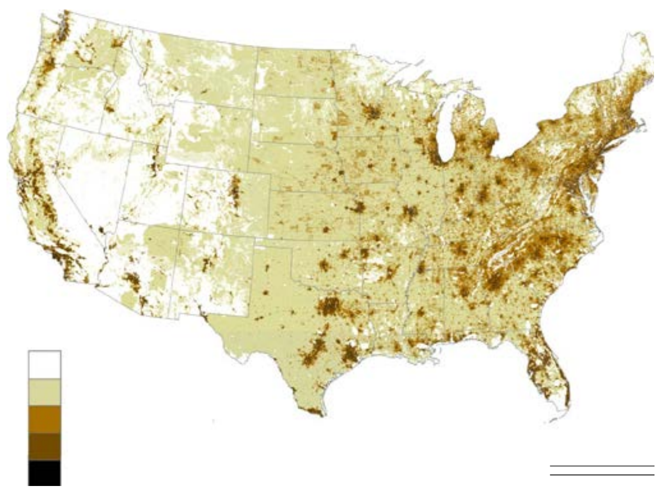
The Department of Transportation's Freight Analysis Framework, based

Figure 3. Housing Density in 2010, With Projections for 2100

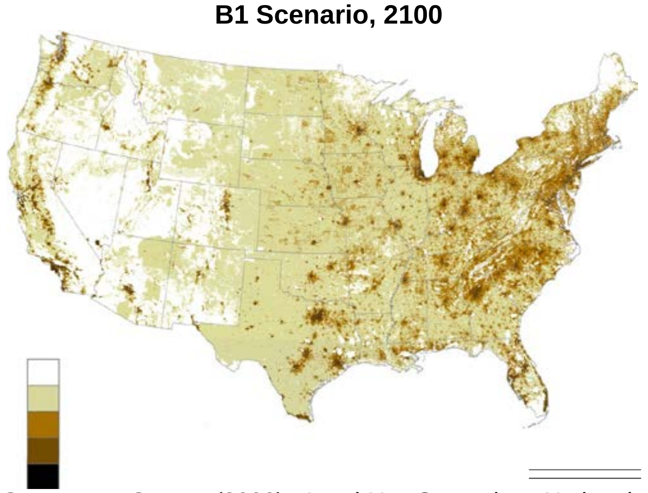
Base Case, 2010



A2 Scenario, 2100



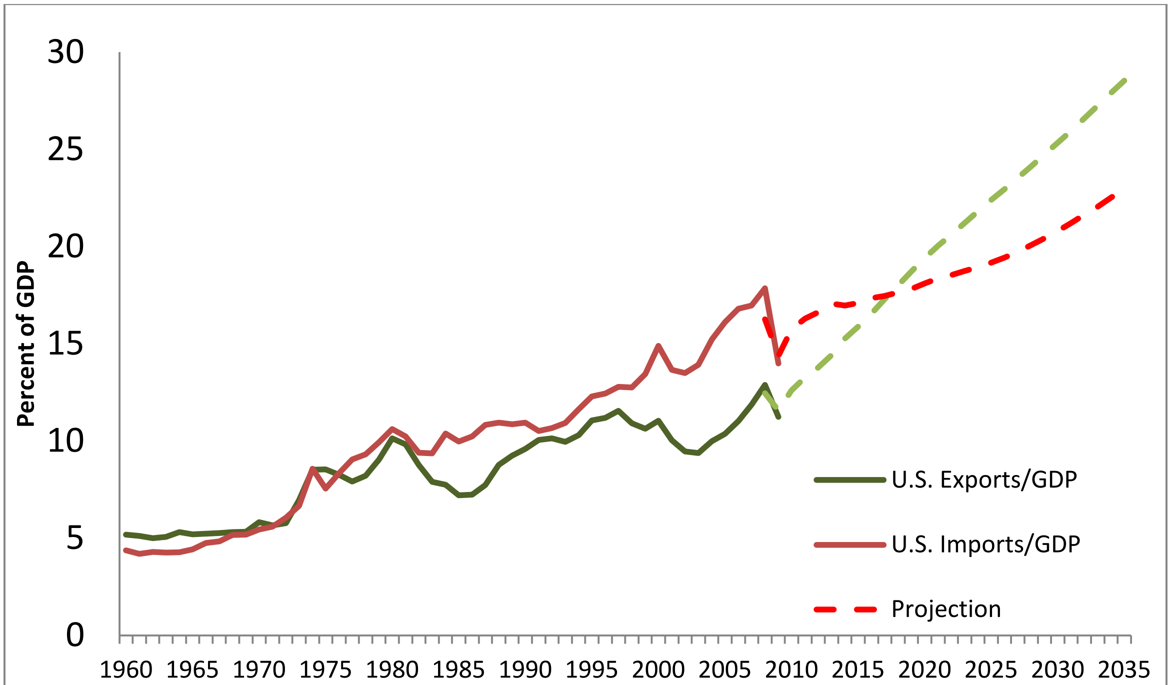
B1 Scenario, 2100



Source: U. S. EPA (2009). *Land-Use Scenarios: National-Scale Housing-Density Scenarios Consistent with Climate Change Storylines*. GCRP, NCEA, Washington, DC. EPA/600-R-08/076F, pp. A-4, A-10, and A-13.

upon a different macroeconomic projection, estimated that U.S. export tonnage would grow by a factor of 2.8 between 2007 and 2040, and that import tonnage would grow by a factor of 1.9.[17]

Figure 4. U.S. Exports and Imports as a Share of GDP, 1960-2009, with Projection to 2035.



Source: World Bank Database, DOE/EIA, *Annual Energy Outlook 2011* Reference Case Macroeconomic Indicators

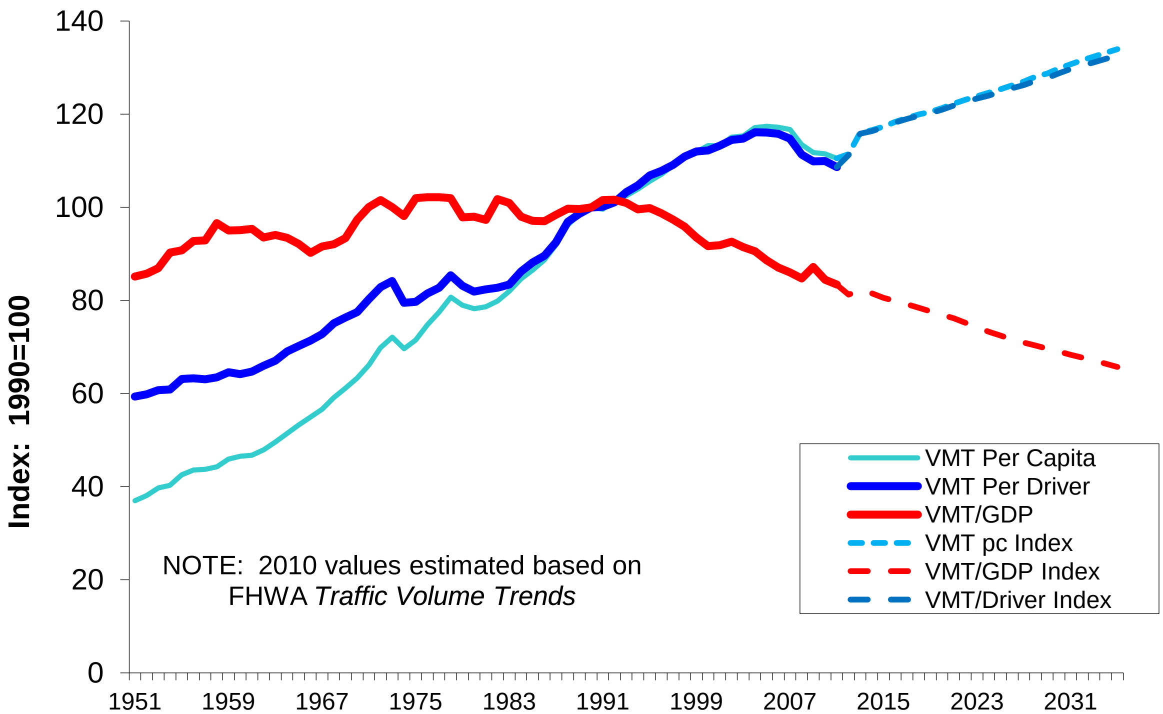
F. **Passenger Travel**

Passenger travel accounts for the bulk of the vehicle miles and person-miles of travel in the United States, and encompasses urban travel, largely by private automobile and transit, and inter-city travel, which incorporates air travel, inter-city rail and bus, and additional personal automobile travel. Personal travel is dominated by private automobile travel. In 2009, some 138 million people commuted to work, 86-percent by private automobile. Public transportation accounted for 5-percent of journeys-to-work.[18] In key cities, however, transit accounts for a large share of commute trips: 36 percent in Washington, DC; 31 percent in Chicago, and 37 percent in Boston.[19] The most recent statistics for long-distance travel ((defined as a trip distance greater than 50 miles) show an analogous pattern: In 2001, private vehicles accounted for 89 percent of long-distance trips.[20] Air travel accounted for only 7 percent of trips, but 40 percent of person-miles traveled. Commercial aviation clearly dominates the longest trips, while automobiles dominate the shortest trips. Inter-city rail and bus accounted for only 5 and 2 percent of both trips and passenger-miles, respectively.[21]

Personal vehicle travel has a central place in U.S. transportation, and will likely continue to do so. Even very large increases in intercity rail and transit market share would have only a modest effect on personal vehicle travel.

Figure 5 shows historical trends of vehicle miles traveled (VMT) per capita in the United States, with projections from the Energy Information Administration through 2035. Historically, VMT has grown rapidly in the United States, though the VMT per capita growth slowed during the 1990s, flattened after 2000, and turned down in 2006, ahead of the onset of recession. The EIA anticipates that VMT per capita will grow only 0.6 percent per year in their reference case, and that includes a post-recession near-term recovery in VMT.

Figure 5. Indices of U.S. Vehicle Miles Traveled, 1951-2011, with Projection to 2035
(1990 = 100)



SOURCE: DOT/FHWA, *Federal Highway Statistics*, various years, and DOE/EIA AEO 2011.

Total VMT will be greatly affected by future population growth, and, as illustrated by Figure 1. There is a considerable range of future population growth rates, which, through employment and household formation, may have a larger effect on VMT growth than per capita trends.

In addition, changes in land use patterns, social preferences, technological innovations, and mitigation measures (which would be more consistent with the IPCC's B1 emissions scenario) may affect personal travel.[22] In EIA's modeling, economy-wide measures that have been recently considered by the U.S. Congress affect the electric power sector to a greater extent than the transportation sector. As part of EIA's modeling of the proposed American Power Act, the scenario with the largest effect on the transportation sector reduced projected 2035 VMT by about 5.6 percent.[23]

Commercial aviation did not exist at the beginning of the twentieth century, and remained of negligible importance into the 1930s. After World War II, however, U.S. commercial aviation combined technological innovation with rapid growth for several decades, outstripping modal competitors such as ocean liners.

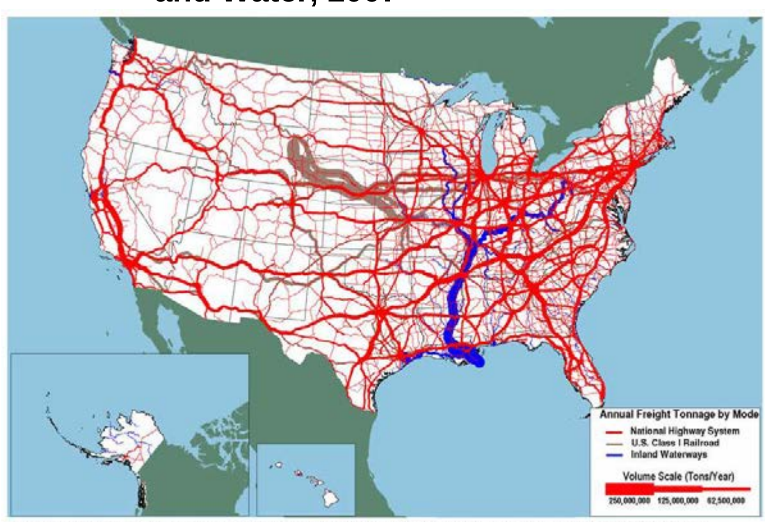
U.S. air passenger miles traveled grew at a 4 percent rate during the 1990s, but during the past decade, the growth has slowed considerably, perhaps due to macroeconomic turbulence and the lingering effects of 9/11. Federal Aviation Administration (FAA) forecasters take the view that, in the long run, long-distance travel (and particularly international travel) will prove increasingly attractive to a wealthier population. FAA projects domestic revenue passenger miles to grow 3.1-4.5 percent per year through 2031, more rapidly than forecast population or GDP growth.[24] An alternative view is that passenger travel has largely saturated, and future growth will be more attuned to population growth and household formation, a view that is more consistent with EIA energy projections, with projected annual growth in available seat miles of 0.8-1.4 percent through 2035.[25]

Both freight and passenger aviation will remain key elements in the transportation system throughout the next century. Modeling of economy-wide domestic emission reduction policies suggests little effect on projections of passenger travel.[26]

G. **Freight**

Figure 6 shows the spatial distribution of freight traffic by mode in the United States, measured as tons of freight moving between origin-destination pairs. The thick brown line connecting Wyoming to the Mississippi represents Powder River Basin low-sulfur coal moving to power plants in the Midwest and South by rail. The thick blue line running down the Mississippi River represents barge traffic, primarily agricultural

Figure 6. Freight Tonnage on U.S. Highways, Rail and Water, 2007



Sources: Highways: U.S. Department of Transportation, Federal Highway Administration, Freight Analysis Framework, Version 3.1, 2010. Rail: Based on Surface Transportation Board, Annual Carload Waybill Sample and rail freight flow assignments done by Oak Ridge National Laboratory. Inland Waterways: U.S. Army Corps of Engineers (USACE), Annual Vessel Operating Activity and Lock Performance Monitoring System data, as processed for USACE by the Tennessee Valley Authority; and USACE, Institute for Water Resources, Waterborne Foreign Trade Data, Water flow asssignments done by Oak Ridge National Laboratory.

commodities for processing and exports. Both of these commodity flows are supported by a large and complex transportation infrastructure, and both are likely to be subject to climate impacts.

A projection by the Federal Highway Administration suggests that total freight tonnage moved will nearly double by 2040, export tonnage will nearly triple, while import tonnage will increase by a factor of 2.5[27] (Figure 7). These projections suggest that the U.S. economy will be larger and even more tightly integrated with the world economy than at present. Inevitably, this more trade-oriented economy will carve out new freight patterns, based on new products and new markets, both at home and abroad.

H. **Economic Evolution and Technological Change**

The general picture drawn from current projections is that the transportation system will look very much the way it does today, only serving more people in a wealthier society. This may be true, but, as the economy and society evolve, transportation systems will evolve with them. In addition to changes in society, the next century will see extensive evolution and technological change in transportation systems themselves.

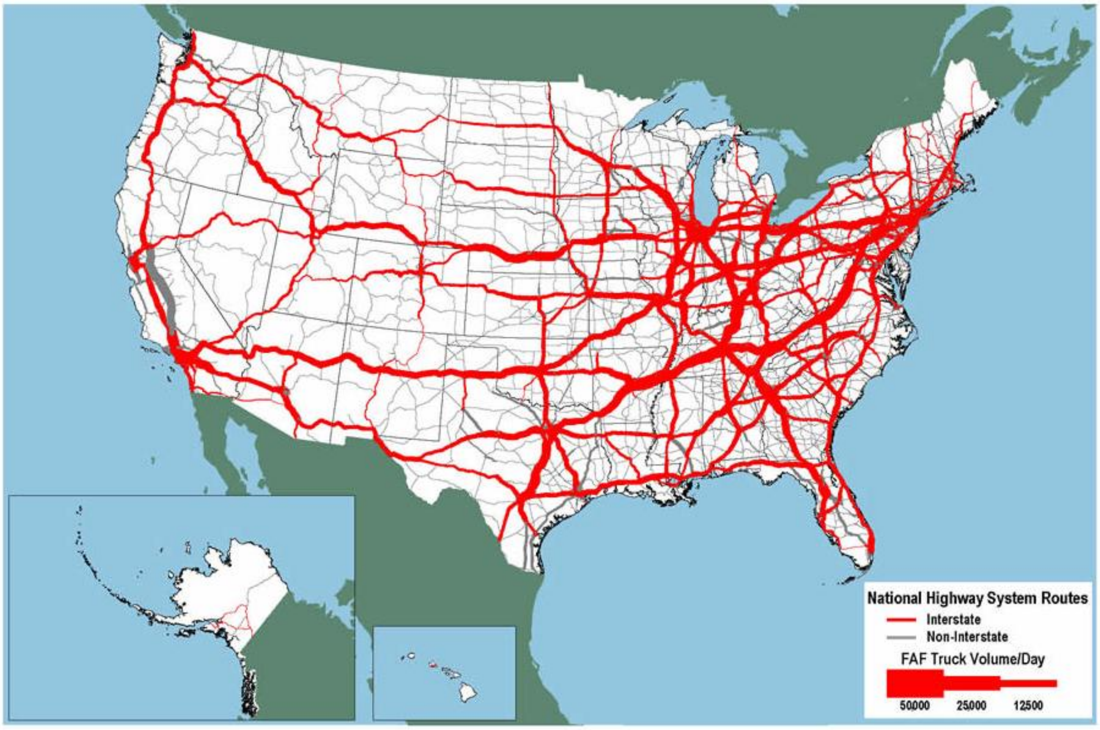
A transportation analyst, working at the beginning of the Twentieth Century, might worry about how a growing society would manage the ever-increasing number of horses needed by urban civilization, and confidently project faster trains, more extensive tram networks, and bigger passenger steamships. He might puzzle over prospects for automobiles, and wonder if petroleum would be plentiful enough to be a useful fuel. But commercial aviation, containerization, and near universal ownership of private automobiles would likely have gone unimagined.

It would be reasonable to expect that vehicles and transportation systems will become smarter, safer, more efficient, and have smaller environmental footprints over time, though the exact path and motivating impetus for change remains uncertain. A wealthier public is likely to place an increasing value on time. The intersection of ubiquitous and inexpensive navigation, mobile communications, and processing power is likely to continue to produce significant innovations in vehicle and transportation systems that will lead to improvements in system performance, safety, and a reduction in transportation's environmental footprint across all modes.

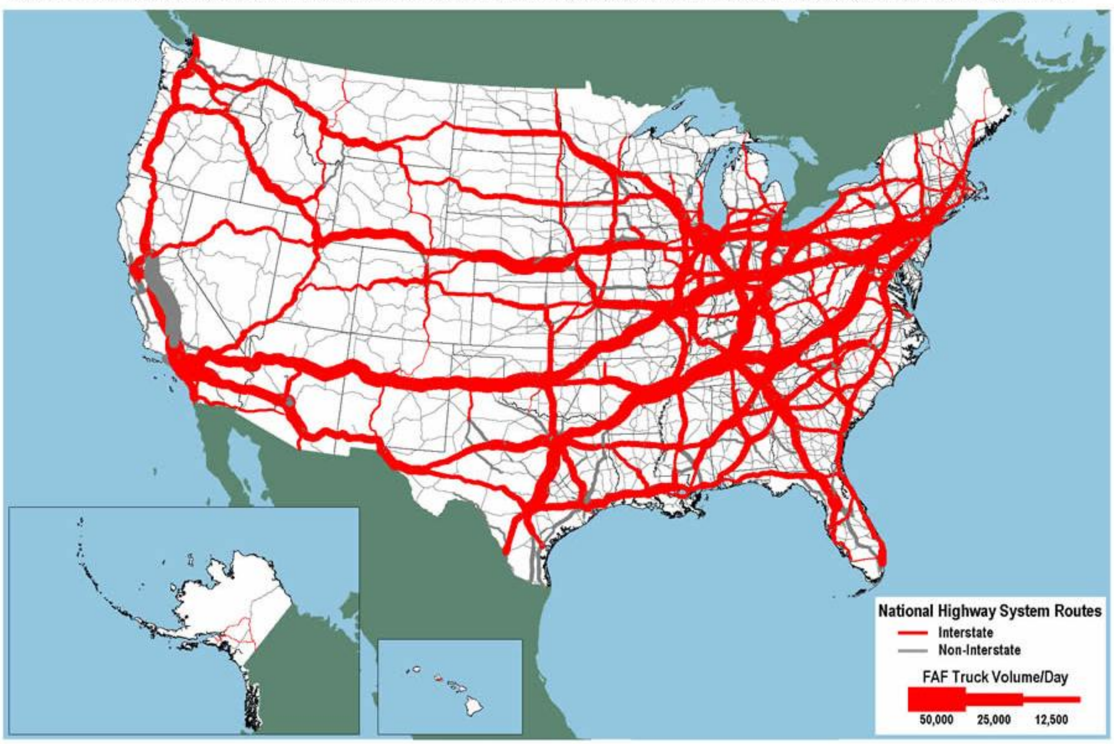
But it is also quite plausible that entirely new transportation systems will emerge, and the usage patterns on existing systems may change dramatically.

There are many possible transportation-systems-in-waiting that could be brought into existence by the right confluence of influences. Economic evolution may well inspire new combinations of existing technologies, or fundamental technological innovations may make new transportation strategies feasible. There will be technological surprises, and transportation systems may evolve in unforeseen ways.

Figure 7. **Average Daily U.S. Truck Traffic, 2007 and Projection for 2040**



Note: Long-haul freight trucks typically serve locations at least 50 miles apart, excluding trucks that are used in movements by multiple modes and mail.
Source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 3.1, 2010.



Note: Long-haul freight trucks typically serve locations at least 50 miles apart, excluding trucks that are used in movements by multiple modes and mail.
Source: U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations, Freight Analysis Framework, version 3.1, 2010.

[7] USDOT, Bureau of Transportation Statistics (2011), *National Transportation Statistics*, (2011), Tables 3-1 and 3-4. BTS estimates of transportation share of final demand are about 10 percent of GDP as of 2005. Purchases of "for-hire" transportation services are about 3 percent of GDP, which exclude the annual cost of transportation services provided within, rather than between, firms, and the public's personal cost of driving. http://www.bts.gov/publications/national_transportation_statistics/#chapter_3

[8] The World Bank Database. See: http://data.worldbank.org/indicator/NE.EXP.GNFS.ZS

[9] *Emissions Scenarios*, IPCC, 2000 - Nebojsa Nakicenovic and Rob Swart (Eds.) Cambridge University Press, UK. p. 20. See: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0. The scenarios have been updated in subsequent assessments.

[10] CCSP, 2007: *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B).* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research]. Department of Energy, Office of Biological & Environmental Research, Washington, DC. http://www.climatescience.gov/Library/sap/sap2-1/finalreport/

[11] U. S. Department of Commerce, Census Bureau, *National Intercensal Estimates, 2000-2010*. http://www.census.gov/popest/intercensal/national/nat2010.html

[12] U.S. Department of Commerce, Census Bureau, *Summary Tables: Projections of the Population and Components of Change for the United States: 2010 to 2050*, (2008). http://www.census.gov/population/www/projections/summarytables.html

[13] Jennifer M. Ortman and Christine E. Guarneri, *United States Population Projections: 2000 to 2050, (Census Bureau, 2009).* http://www.census.gov/population/www/projections/analytical-document09.pdf downloaded 11 October 2011.

[14] U.S. Department of Commerce, Census Bureau, "Population Projections of the United States by Age, Race, Sex, and Hispanic Origin, and Nativity, 2000 to 2100," (January 2000). http://www.census.gov/population/www/projections/natsum-T1.html

[15] U.S. Department of Commerce, Census Bureau (2008), *2008 U.S. Population Projections.* http://www.census.gov/population/www/projections/2008projections.html

[16] U.S. Environmental Protection Agency, (2009). *Land-Use Scenarios: National-Scale Housing-Density Scenarios Consistent with Climate Change Storylines*. GCRP, National Center for Environmental Assessment, Washington, DC. EPA/600-R-08/076F. See: http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203458#Download

[17] U.S. Department of Transportation, Federal Highways Administration, Freight Analysis Framework (Version 3) Data Extraction Tool. http://faf.ornl.gov/fafweb/Extraction3.aspx

[18] USDOT, Bureau of Transportation Statistics (2011), *National Transportation Statistics*, Table 1-41. http://www.bts.gov/publications/national_transportation_statistics/html/table_01_41.html

[19] U.S. Department of Commerce, Census Bureau, *American Community Survey 2010.* http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml#none

[20] USDOT, Bureau of Transportation Statistics (2011), *National Transportation Statistics*, Table 1-42. See: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_42.html

[21] Long-distance trip data (from the National Household Travel Survey) has not been updated since 2001. More recent data from other sources suggest that bus travel has doubled since 2001 and 2009 while, air travel increased about 13 percent, and inter-city rail travel has been flat. Long-distance personal vehicle travel is unknown, but total light duty passenger-miles traveled have increased only 9 percent. Personal vehicle travel probably still dominates long-distance travel.

[22] There have been several recent reports by DOT and others on policy measures for reducing greenhouse gas emissions in the transportation sector. Cf: US Department of Transportation, Climate Center, *Transportation's Role in Reducing Greenhouse Gas Emissions*, (April 2010), http://www.reconnectingamerica.org/assets/Uploads/2010DOTClimateChangeReportApril2010.pdf

[23] USDOE/EIA, *Energy Market and Economic Impacts of the American Power Act of 2010* (July 2010). See: http://www.eia.gov/oiaf/servicerpt/kgl/index.html. The scenario with the largest change in VMT is the "No International Offsets/Limited Alternatives" case. This report is based the EIA's *2010 Annual Energy Outlook*, which has reference case 2035 VMT about 5-percent higher than EIA's *2011 Annual Energy Outlook*.

[24] USDOT, Federal Aviation Administration, *FAA Aerospace Forecast: Fiscal Years 2011-2031*, (2011). The quoted figure is the range of optimistic/reference/pessimistic cases for U.S. carrier revenue passenger miles. In the FAA projections, international travel grows more rapidly (near 5 percent), while domestic travel grows at a 2.8 percent annual pace. See: http://www.faa.gov/about/office_org/headquarters_offices/apl/aviation_forecasts/aerospace_forecasts/2011-2031/

[25] USDOE/EIA, *Annual Energy Outlook 2011*. See: http://www.eia.gov/analysis/projection-data.cfm#annualproj

[26] USDOE/EIA, *Energy Market and Economic Impacts of the American Power Act of 2010* (July 2010). http://www.eia.gov/oiaf/servicerpt/kgl/index.html.

[27] USDOT, Federal Highways Administration, Freight Analysis Framework, Version 3. Comparison with 2009 vs. 2040. http://faf.ornl.gov/fafweb/Extraction2.aspx

III. Direct Impacts

A. **Overview**

The range of weather events within a particular region determines the choice of construction materials, operations management, vehicle design, and even the dominant mode of travel. Tundra climates, for example, often contain unpaved roads because few pavements materials can withstand the freeze-thaw cycle while the extreme cold of tundra makes rail unviable.[28] Inhabitants expect snow and extreme cold, and ensure that adequate snow-clearing equipment is available. Municipal and State agencies routinely expect and budget for snow clearance. Similarly, motor vehicles and trucks frequently have special modifications for cold-weather performance (oil and radiator heaters, for example), and tend to be chosen for drivability in snow.

At the opposite end of the thermometer, pavement, bridges, and rail lines generally deteriorate faster at temperatures higher than 90° F in the north and 100° F in the south. Public and private buildings have architectural modifications to accommodate heat, including sunshades, light colors, and heat resistant materials. Vehicles may have oversized radiators and air conditioning is nearly universal.

Historically, transportation planners and engineers have accommodated the anticipated range of weather effects, including extreme events, by examining historical experience. For example, bridges may be designed to withstand "50-year floods," a classification created to describe the magnitude of a flood that occurred about once every fifty years in the past, or put another way, assuming that the distribution of past events is an accurate prediction of future events, that there is 2 percent annual probability that a flood of this magnitude or greater will occur.[29]

Infrastructure designers and system operators have to decide both about average conditions, and just how much physical insurance against extreme events to build into their designs. In this calculation, climate influences transportation planning and ultimately transportation operations, through multiple paths:

- A changing climate will make changes in infrastructure, vehicles, and operations desirable over time.

- Changes in the variability of climate will affect how much physical insurance in the form of design margins that system designers must build to achieve a given level of risk.

- An increase in the uncertainty of future climate will increase the riskiness of infrastructure investments and transportation operations. It may become more difficult to optimize facilities under conditions of increased uncertainty.

Climate change is causing deviations in historical weather patterns, and the deviation will increase with time. The likelihood of future events can no longer be predicated upon historical data and will instead be characterized by increased uncertainty. What was previously a "50-year flood" in a given geographic area may become a "30-year flood" in 2050 or an "8-year flood" in 2100.

Under these conditions, infrastructure design will become increasingly sensitive to assumptions about the expected life of facilities. For a given level of lifetime risk, a facility may need to be much more robust if the designers assume a 50-year life than if the designers assume a 30-year life.

However, other factors may interact to stretch out the actual life of transportation infrastructure. If the U.S. population and the transportation sector grow slowly, with relatively little technological change, the pace of functional obsolescence will slacken. Replacement or repair of public infrastructure is partly a function of public investment decisions, and is likely to be influenced by long-term fiscal conditions.

Hence, infrastructure designers and operators may have to trade off between more robust replacement or refurbishment designs for a smaller number of individual facilities, or less robust designs for a larger number of facilities. Further, operators of critical infrastructure and/or clusters of facilities subject to emergent climate risks may decide to accelerate routine replacement or refurbishment of such facilities.

Beyond the piecemeal replacement or refurbishment of existing infrastructure, new infrastructure will be developed. New developments will reflect not only changing land use patterns, economic, and population growth, but climate effects and technological innovations. New infrastructure and transportation systems will face the same design trade-off between risk, cost, and reliability faced by existing infrastructure operators.

Infrastructure operators will face a powerful temptation to assume some extra long-term risk, and defer climate-related upgrades. However, such decisions will have a cumulative long-run impact, since deferred upgrades will gradually reduce the reliability of transportation systems, and create a future backlog of unimproved facilities that have gradually become critical risks.

Table 2 summarizes the most important direct effects on transportation systems. These effects are discussed at greater length below.

Table 2. Properties of Direct Infrastructure Risk to Climate Change*

	Effects from known extremes		Effects from gradual change in distribution	
	Effects	Potential Adaptation	Effects	Potential Adaptation
Temperature	Heat wave extremes Buckled rails & pavement Transit operation mechanical failures Bridge expansion Cracked pavement Freeze-thaw cycles Subgrade soil caving Frost heave Increased drought/wildfire Infrastructure damage, mudslides	Minimum short-term impact on pavement Full-depth patches in roadway repair Use of heat resistant materials for new projects Retrofitting of materials and designs	Wider temperature ranges Structural stress from contraction/ expansion cycles Warmer overall temperatures Decreased snow and ice removal cost Faster depreciation of various infrastructure Thinning sea ice; opening of Northwest passage Pipeline instability	New standards in load/pavement engineering Research in materials Use of risk-based probabilistic planning research into Arctic areas Discourage building in fire-prone areas
Flooding/ hydrologic change	Coastal storm surges/Inland flash flooding Tunnel & underground flooding Shutdown of roadway links from flooding Bridge collapse, scour Culvert damage Airport delays Transit facility flooding	Enhanced warning systems Levee building Improved drainage systems Raise, protect Modify, protect Replace, resize Drainage, protection Relocate, drainage	Sea level rise Permanent inundation Greater risk to storm surge Heavy precipitation Potholes due to saturated soils More flash flooding	Research on greatest risk areas Development away from risk-prone areas Research on drainage design Relocation of high-risk networks Increased network redundancy
Systemic effects/ Change in transportation flows	Various extreme events Evacuation route blockage Shifts in production and development Changed transport flows from immediate drought- or wildfire-related effects	Multiple evacuation routes, multiple disaster plans Enhanced disaster response capabilities Incorporation of climate change into infrastructure currently being replaced Relocation of extreme-risk sites	Greater inland development Increased need for transportation infrastructure Other economic changes Northwards shift in agriculture Changing river hydrology Varied access to inland water channels/low water levels	Infrastructure construction in inland areas Diversification of demand for various links Research and analysis

*Note: "Effects from known extremes" broadly encompasses three concepts: 1. Effects of extreme events, 2. Effects occurring at the present or the near future, and 3. Acute impact to infrastructure and appropriate tactical responses. "Effects from gradual change in distribution" encompasses a supplementary set of ideas: 1. Effects resulting from overall movement of distribution, 2. Effects occurring over many years, and 3. Impacts to the overall transportation network and appropriate strategic changes. Note that effects described under both categories may occur both in the immediate future and the long-term future, but the latter category is focused on long-term strategy.

B. **Temperature and heat**

The primary effect of increased greenhouse gas emissions is increased global temperatures due to the greenhouse effect. Temperature affects nearly every component of infrastructure design by forcing materials to contract and expand. Climate-related temperature effects will manifest themselves in complex and consequential regional scale patterns. For a given increase in global average temperature, overland temperatures are likely to increase more than over-ocean temperatures. High latitude temperatures are increasing more rapidly than at lower latitudes. Temperature increases will be distributed unevenly across seasons, regions and night versus day. The most important direct impacts for transportation systems are winter temperatures that shift precipitation from snow to freezing rain to ordinary rain, peak summer daytime temperatures, and high latitude winter temperatures sufficient to melt permafrost.

Temperature impacts are likely to unfold gradually over a period of decades, with smaller effects in the near future and larger effects in the more distant future. The scale of effects in the distant future depends, in part, on the level of global emissions in the intervening period.

Currently, many temperature-related damages come from stresses due to extreme thermal expansion and contraction. Breaks, buckling, blowup, or heat kinks occur when there is not enough room for thermal expansion, causing heat-sensitive material such as rail lines to thrust out or upwards.[30] The July 2010 east coast heat waves, for example, caused heat kinks in the Washington Metro and Boston "T" rails so that certain sections had to be replaced.[31] In some cases, the risk of derailment during periods of excessive heat will cause rail system operators to reduce train speeds, causing delays and lowering system capacity even in the absence of an actual derailment.[32] Pavement is also subject to buckling, although its threshold temperatures are often higher than those of rail.

Rails are adapted to high temperatures through setting "rail-neutral temperature" standards. Rails are often pre-stressed at 100° F in the south and 90° F in the north so that they will acclimate to these temperatures.[33] Research on rail engineering has reduced the number of rail break incidents, and improve engineering practice will gain in importance with increased temperatures.

However, it is difficult to pre-stress materials so that they are adapted to both extremely high and extremely low temperatures. Pre-stressing for thermal expansion, for example, often means that the material will be unable to withstand extreme contraction from very low temperatures.[34]

In Alaska, summer thawing of permafrost is putting transportation infrastructure at risk, incluing including rural road and airstrips. The Trans-Alaska Pipeline System extends more than 400 miles from Prudhoe Bay in the north to the ice-free port of Valdez in the south, and is elevated on vertical supports over potentially unstable permafrost. Because the system was designed in the early 1970s on the basis of permafrost and climate conditions of the 1950 to 1970 period, it requires continuous monitoring and some supports have had to be replaced.[35]

Heat can also often lead to electrical or mechanical failures as well as discomfort or health risks for transit passengers and workers. The extensive and complex electrical control, monitoring, and communications systems in aviation, maritime, and rail transportation systems as well as the electro-mechanical systems within surface vehicles are sensitive to overheating. Ventilation and cooling for systems such as signal rooms and electrical boxes are often designed with the region's historical climate in mind. Recent years have led to an increasing number of overheating incidents for areas with historically mild temperatures. For example, Portland's TriMet electrical substations provide cooling adequate in weather up to 90° F, which has recently proved inadequate for high heat days. With higher temperatures, TriMet also reports that stainless steel ticket vending machines now tend to overheat in direct sunlight, as does electrical equipment located under the roof of low-floor rail vehicles.[36]

Higher temperatures may also lead to increased probability of wildfires. Increases in temperature may cause annual mean area burned in the western United States to increase by 54 percent by the 2050s compared to the present day. Though the frequency of wildfires will decrease in certain regions, the frequency in others may increase by as much as 178 percent.[37] In a worst case scenario, drought, high temperatures, and rainless winds act together to create a perfect firestorm. For example, the Texas wildfires of September 2011, which destroyed over 1400 homes, was sparked by scorching temperatures and a prolonged drought, which was greatly exacerbated by the winds of Tropical Storm Lee.[38]

Higher temperatures may reduce productivity among transportation and construction workers, and if not managed, may also pose health risks.[39]

In addition to workers, travelers would be potentially exposed to increased heat stress. As noted in Chapter II, the U.S. population is projected to contain an increasing share of people who are over 65, and hence less likely to be driving private vehicles and more likely to be vulnerable to heat stress when traveling. While public transportation systems are very likely to be air conditioned when necessary for comfort, greater average temperatures and a more fragile population pose an increased health risk if and when transportation systems fail, implying that maintaining travel reliability may have a growing public health dimension.

Wildfire can be hot enough to damage road pavement, burn railroad ties, and destroy lighting and signs. In addition, loss of land cover can cause subsequent erosion and landslides. Dead standing timber can fall and block roads.

Current temperature extremes would not require wholesale replacement of rail and pavement: replacement is likely to occur as a part of normal maintenance, upgrade, or retrofit processes.[40] Most rail and pavement projects have a lifespan of 15 to 25 years, which would allow for a "wait-and-see" approach and replacement with more robust materials at the end of a project's lifespan.

However, by the end of the century, the average U.S. temperature is projected to increase by approximately 7 to 11° F under a high emissions scenario and approximately 4 to 6.5° F under a lower emissions scenario. A "20-year heat wave" at present would occur every other year on average by 2100.[41] By the second half of the century, it is likely that the shift in the distribution of temperatures will prompt revised design assumptions for pavement and bridges and technological breakthroughs in heat-resistance in order for a variety of transit, maritime port, and airports functions to avoid frequent failure.

Bridges present special challenges because of their great expense and long life spans. Not only are today's aging bridges already vulnerable because to a range of environmental conditions for which they were not designed, but bridges being built today will face a greater range of environmental conditions, including higher average temperatures, over their lifespan.

C. Precipitation and flooding

Increases in temperature significantly alter the hydrologic cycle. However, the analysis of water-related changes is more complicated than predictions of future temperature because higher temperature leads to both increased evaporation and higher humidity. Thus, changing climate may be reflected in increases in both drought and pluvial events. Two especially important water cycle-related effects with respect to transportation include relative sea level rise, which will occur gradually over the next century, and more intense hydrological events. The water holding capacity of air increases by about 7 percent with every 1° C increase in temperatures, thus leading to more intense rains. "It never rains, but it pours!" may very well describe precipitation events in the future.[42]

The 2008 Global Change Research Program (GCRP) report on weather and climate extremes listed accumulated evidence from multiple sources of increases in precipitation intensity across much of the United States.[43] Precipitation intensity is important because the pattern of precipitation has a large effect on surface run-off, and surface run-off is what causes flooding. Flooding, in turn, can damage a range of transportation infrastructure. Most communities have extensive storm-water water runoff systems that will generally have some maximum design capacity. When the capacity of these systems is exceeded, infrastructure can be temporarily closed or damaged. Even without flooding or damage to infrastructure, increased storminess will reduce capacity and increase congestion, with economic costs both for individuals and for freight movements.

Precipitation, flooding, and extreme weather pose multiple hazards to transportation systems.

- Existing bridges, roads, culverts, rail lines, airports, and many other elements of transportation infrastructure have been designed for some maximum level of flooding. When design levels are exceeded, the result may range from temporary closure to destruction. Destruction of infrastructure can create delays and reduce capacity for months or years while damage is repaired.

- Faced with increased frequency of extreme events, designers of new infrastructure must choose some combination of equal reliability at higher cost or lower reliability at equal cost. Designers who ignore climate impacts have probably implicitly chosen lower reliability at equal cost.

- Flooding has an important safety component. During 1970-1999, at least 23 percent of acute hurricane deaths were due to people trying to drive in flood waters.[44]

- Even in the absence of hurricanes, some 24 percent of automobile accidents and 17 percent of fatal accidents (7,130 deaths per year) over the period 1995-2008 were defined as "weather-related," meaning they occurred in the presence of inclement weather, mostly (75-percent) defined as "wet pavement.[45] Several studies have shown greatly increased accident risk for light duty vehicles in bad weather.[46] Heavy trucks also appear to be at greater weather risk for fatal accidents than light duty vehicles.[47] Accidents, of course, cause temporary reduction in roadway capacity and throughput.

- Flooding leads to lane and road closures, and even heavy rainfall reduces road capacity. Light rain reduces freeway capacity 4-11 percent while heavy rain reduces capacity by 10-30 percent through a combination of reduced speed and congestion.[48] Chin et al (2004) estimated that adverse weather accounted for 9 percent of national traffic delay from non-recurring causes (as of 1999).[49] Accidents accounted for about half of delay, so congestion is one of the indirect consequences of weather-related accidents.

- Weather is currently a significant source of commercial flight delays, accounting for 37 percent of delayed operations and 39 percent of delay minutes during the period June 2003 – October 2011.[50] Both total delays and delays attributable to weather have declined over the past eight years. While some weather delays are caused by extreme events, the bulk of weather delays emanate from the National Air Space System, as delays propagate through the system.[51]

The frequency of flooding and drought in inland areas is likely to increase. The relationship between precipitation and surface water flows is complex and site-specific. A recent conference report by the National Research Council investigates this question in more detail.[52] The report's finding section observes that, despite increasing precipitation across much of the United States, that a USGS "analysis of flood occurrence (i.e., the annual maxima series) shows essentially no trends at a set of U.S. Geological Survey (USGS) stream gages that were carefully selected to minimize any influences of water management.[53]

The 2011 Missouri River summer floods, for example, were caused by precipitation 600 percent greater than normal.[54] The floods lasted over three months and lead to the closure of more than 10 bridges, making it impossible to cross the Missouri River for more than 100 miles. Several rail lines were rendered impassable. As a result, travelers as well as thousands of tons of freight had to be rerouted.[55]

Because of increased evapotranspiration rates in certain regions, water levels in the Great Lakes are projected to fall, while water levels in the Mississippi may fall due to periodic drought, which might increase costs for freight shipment via barge.[56] [57] With greater climate variability, the risk of flooding rivers may increase along with drops in the water level. The effect on agricultural transportation flows will be discussed in Chapter IV.

Flooding and heavy precipitation may affect transportation infrastructure in several ways. Bridges and underground stations are especially at risk. During heavy precipitation events, bridges are assailed from all sides – column foundations are threatened by scour, a process in which the river and steam bed near the foundation is eroded by volatile currents; buoyant force from rising water levels could tear bridge tops from columns; and winds and wave action pound the sides of the bridge.[58] The nation's aging infrastructure is another factor which greatly increases infrastructure risk to climate change – nearly 11.5 percent, or 69,223 of the nation's bridges with an average of over 280,000,000 vehicles in average daily traffic, are already structurally deficient.[59]

As bridges are replaced or repaired, a number of different adaptation mechanisms are possible. The life span of the typical bridge is set at 50 years while the current average national bridge age is 42 years. Bridges can last much longer. Of the 55,000 bridges on the interstate highway system in 2006, 5 were built prior to 1900, and 1,400 bridges were built prior to 1950.[60] Thus, while bridge designs are subject to modification as they are replaced or repaired, some fraction of bridges built today can reasonably be expected to be in service in 2100.

Scour, the most frequent cause of bridge failure, can be reduced by strengthening subsurface conditions. Meyer suggests innovative research could potentially lead to "smart infrastructure" which is able to direct turbulent flow away from column bases.[61] Bridge heights could be increased to a precautionary level.

Stronger, more stable materials and design changes could defend against wave and wind action. Transit and other transport hubs also face serious risk from water-related events. Tunnels and subway systems, in particular, may become collecting pools for runoff because of their low elevation. As the first line of defense, designs that prevent water from first entering, such as elevated entry points and ventilation, could be built or retrofitted. As a second line, additional pumping capacity, already installed in subways in New York City, Washington, DC, and many other major cities, may be added.[62]

Highways and roads are also at risk from water precipitation. In addition to bridge scour, heavy rain can cause subsurface soil to compact and sink.[63] Landslides and erosion can also damage roads and railroads, particularly when natural land cover has been disturbed.

Eventually, flood risks in areas with accelerated relative sea level rise will morph into permanent inundation risks by late century, particularly where local geology and wave action promote rapid erosion, as discussed in Section F, below.

D. **Drought**

Drought is another possible outcome of climate change, and also of climate variability. A more variable climate may be wetter on average but with longer periods of drought.

For waterborne transportation systems, drought is primarily an issue for the Midwest. There are direct impacts on water levels along navigable waterways, particularly the Mississippi/Missouri/Ohio complex. Drought may also produce indirect effects on transportation systems by affecting agricultural production or land use patterns.

While most regions of the United States are likely to experience increased precipitation, and increased exposure of extreme events, the Southwest appears likely to experience reduced precipitation, which may reduce weather impacts on transportation system safety, reliability, and capacity. On the other hand, systems may experience more heat impacts. Drought would also increase the frequency of wildfires. In some cases, falling water tables may affect the load-bearing capacity of soils, and disturb roadbeds and buried pipelines, as has been reported in Texas.[64]

E. **More Intense Hurricanes**

Hurricanes are among the most destructive natural phenomena encountered in the United States. The relationship between hurricanes and climate change has been extensively discussed within the scientific community. Since warmer air can contain more moisture, a warmer climate will generally have more potential energy. Higher ocean surface temperatures also promote hurricane intensity, so there are a priori reasons for expecting a warming climate to be associated with more hurricanes and greater intensity. However, interpretation of the available data is complicated and subject to debate within the scientific community. Because hurricanes formation, intensity, and tracks are subject to considerable natural variation, a long series of consistent data is required to be confident that one is observing a trend rather than a random variation. However, the long-run historical record is imperfect, particularly prior to 1970, which makes drawing conclusions difficult.

The Global Change Research Program in its 2008 Synthesis report, after reviewing the available information and scientific literature, found that:

> "Atlantic tropical storm and hurricane destructive potential, as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased….This increase is substantial since about 1970, and is likely substantial since the 1950s and 60s, in association with warming Atlantic Sea Surface Temperature.[65]

The report concludes that greenhouse gas emissions "very likely" contributed to increasing sea surface temperatures in hurricane formation regions, and that there is strong statistical correlation between sea-surface temperatures and hurricane intensity. The authors write:

> "For North Atlantic and North Pacific Hurricanes, it is likely that hurricane rainfall and wind speeds will increase in response to human-caused warming."

However, the authors note that there has been no detectable increase in the intensity of the sub-set of Atlantic hurricanes that actually make landfall, and discuss other considerations, such as increased vertical wind shear, that may tend to limit increases in hurricane intensity.[66]

Not only are hurricanes a significant risk factor in coastal areas, through storm surge, flooding, and wind effects, but hurricanes will interact with other climate effects, particularly sea level rise (see following section). In addition, increasing suburbanization (See Chapter II) is likely to increase storm water runoff from hurricane and other severe storm events, unless ameliorated by improved storm water management systems. For the transportation sector, the primary risk from hurricanes is damage to transportation infrastructure, as well as service interruptions from flooding or downed trees, plus secondary impacts from loss of utilities or personnel evacuations.

One of the key lessons of Hurricane Katrina was that many inland bridges had been designed to withstand riverine flooding, and proved unable to withstand the wave action associated with storm surge.[67] In Hurricane Katrina, over two dozen bridges sustained serious damage from wave action, including, most spectacularly, the Bay St. Louis Bridge, which was destroyed and had to be replaced at a cost of $267 million.[68]

In recent decades, the death toll from hurricanes in the United States has been greatly reduced, including reductions in deaths from storm surge.[69] While mass evacuations of threatened coastlines have likely made an important contribution, they are not without their own risks. Mass evacuations place unique demands on transportation infrastructure and transit agencies. Disaster management and transportation agencies have developed complex strategies to sustain mass evacuations.[70]

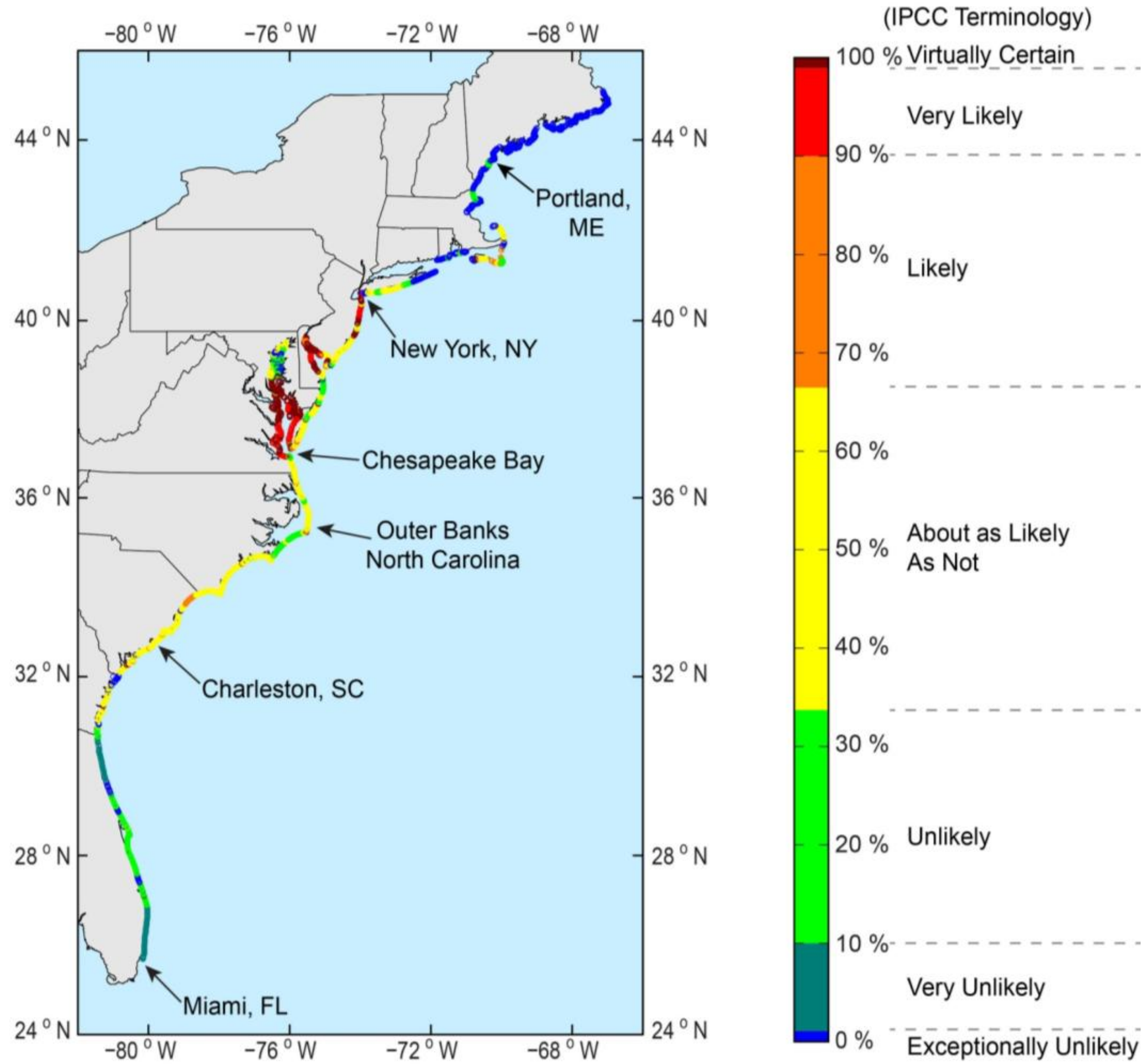
F. **Sea Level Rise**

Relative sea level rise denotes the combined effect of land subsidence and sea level rise. Temperature causes sea level rise most directly through thermal expansion. The most recent IPCC assessment in 2007 estimated a global sea-level rise of 18 to 59 cm (8 to 24 inches), based on thermal expansion alone.[71] Modeling since then has also incorporated second-order effects such as changing ocean circulation patterns[72] and the melting of ice sheets and significant chunks of the Greenland shelf.[73]

Both the Department of Transportation's Federal Highway Administration and the U.S. Army Corps of Engineers have issued guidance on global sea level rise. Federal Highways cites four different recent studies (including the 2007 IPCC assessment) giving a range of possible sea-level rises. The range of projections (spanning multiple IPCC scenarios) is 0.18 – 2 meters.[74] The National Climate Assessment anticipates a mean global sea-level rise of 1.4 meters (4.6 feet, or 54 inches) by 2100.[75]

Sea level rise is combined with the effect of subsidence, which is the sinking of land beneath the ocean. Many areas on the Gulf Coast and the Chesapeake, for example, are subsiding while areas of the West Coast are uplifting.[76] Recent research indicates that other important climate-related factors may affect the consequences of sea-level rise. In particular, shore line erosion appears to be induced by the interaction between sea-level rise, wave action (particularly from storms) and local geology. Figure 8 illustrates the results on recent research on erosion probability along the Atlantic Coast taking these three factors into consideration. Figure 9 shows this phenomenon in action: State Highway Route 12, on Hatteras Island, North Carolina, was washed out in August 2011 when storm surge from Hurricane Irene cut five new channels between the Atlantic and Pamlico Sound.

Figure 8. Probability of Atlantic Coast Shoreline Erosion > 2 Meters/Year



Source: Benjamin Gutierrez, Nathaniel Plant, and Robert Thieler, "A Bayesian Network to Predict Sea Level Rise: Data Report," (USDOI/USGS, Data Report 201-611, November 2011), p. 12. See: http://pubs.usgs.gov/ds/601/

Though the east coast as a whole is more vulnerable to sea level rise than the west coast, low-lying areas such as San Francisco Bay, the Chesapeake Bay, and Cape Cod all face serious risk of flooding and even permanent inundation from sea level rise. Overall, nearly 10 percent of the land area of 180 municipalities resides below 1 meter and is therefore at serious risk to permanent inundation. Nearly a third of the land area in these cities is below 6 meters and is at risk to frequent flooding due to combined storm surge and sea level rise throughout the century.[77]

The risk to coastal cities from sea level rise is compounded by an increase in the intensity of precipitation, tropical storms, and hurricanes, thus increasing the frequency and intensity of storm surge. Tropical storms, hurricanes, and other coastal storms are likely to become stronger,[78] although it is unclear whether the number of storms that will make landfall will increase.[79] Tropical storm tracks may shift northward, where hurricanes have been historically uncommon. These storms hold the potential to cause additional damage in areas that are not well prepared for hurricanes.

Figure 9. Breach of Route 12, Hatteras Island, NC by Hurricane Irene, 2011

Source: NASA. http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=51960

In the Gulf Coast, The USDOT Gulf Coast study determined that 27 percent of the major roads, nine percent of rail lines, and 72 percent of ports are at or below four feet in elevation and are at risk to flooding within the first half century and perhaps even permanent inundation by the end of the century.[80]

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[60]U.S. Department of Transportation, *2008 Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance*, (USDOT: 2008), p. 3-22. See: http://www.fhwa.dot.gov/policy/2008cpr/ There are more than half-a-million bridges in the United States. A historic bridge group identifies a one U.S. bridge built in 1697 and four Eighteenth Century bridges currently open for traffic. See: http://bridgehunter.com/category/year

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IV. Climate Impacts on Transportation Systems

A. **Overview**

This chapter describes climate impacts that affect U.S. transportation systems, rather than individual assets. Transportation systems exist to serve the larger economy and society. As society evolves, transportation systems evolve to move people and goods to where they are needed. While changing climate will inevitably have physical impacts on transportation systems, climate-induced changes in the larger society that are not considered in this report may also affect transportation systems.

B. **Land Use Changes**

Climate-change induced land use changes have the potential to induce significant changes in transportation systems, but such changes are particularly difficult to predict. However, the potential importance of the topic is sufficient that an enumeration of some of the important pathways by which climate may influence settlement patterns, and settlement patterns influence transportation systems may be useful.

Macro-scale land use studies suggest that people are attracted to mild climates, particularly the prospect of warmer winters and milder summers.[81] Current regional population forecasts show slow population growth in the Midwest and Northeast, and much more rapid growth in the South and Southwest.[82] However, with the southern United States gradually heating up, and milder winters in the Northern United States, population and economic activity may tend to shift northward. Reduced precipitation in the desert Southwest may also tend to restrain some categories of economic activity and population growth in that region. Any such shifts will inevitably affect the future pattern of transportation system development.

In addition, increased urban population density (possibly caused by changes in relative prices, social preferences, public policy, or technological change) can cause reduced personal travel distance (as measured in VMT) and induce mode switching from private automobiles to transit.

Threats appear to be most acute where subsidence coexists with sea level rise: along the Gulf Coast and the Chesapeake Bay. Some barrier islands may also be under increasing stress, due to sea level rise, salt water intrusion, and storm effects. Communities, infrastructure providers, insurance companies, and individuals will all be making individual and collective decisions on where to defend, where to adapt, where to defend, and where to abandon facilities and property.

C. **Urban Transportation Systems**

A large fraction of the U.S. population lives in cities and suburbs, and most American's most frequent interaction with transportation systems comes from routine trips to work, school, and shopping, mostly by private automobile or transit systems.

The climate impact on urban travel as a system has been relatively little studied. There is a large and growing literature on climate impacts on transportation infrastructure, but much less work on climate impacts on urban transportation system performance. Two recent studies, one covering Boston, and one using Portland, Oregon consider delay costs from future climate induced flooding. In both cases, the apparent costs are low. The Boston study indicates losses of $100 million from climate-related flooding induced delay.[83] The Portland study does not calculate economic costs, but the amount of increased delay from climate change is so small that the costs would have negligible if calculated.[84] These two studies examine road system delay effects from climate-induced flooding in isolation.

A recent report (Rosenzweig et al, 2011) includes a case study of the impact of a 100-year storm combined with sea level rise on transportation systems in New York, flooding major tunnels.[85] The study's multi-billion dollar damage estimate, while not detailed, illustrates that damage sufficient to immobilize a major city may be very costly.

As described in Chapter III, multiple climate impacts may affect urban transportation systems. To recapitulate, the principal climate impacts on urban transportation system are likely to be:

- Increased intensity of precipitation may induce flooding. Flooding can temporarily reduce capacity and reliability both by closing roads, bridges, and transit systems directly, and cause prolonged interruptions through damage to infrastructure.

- Increased temperatures may affect the reliability of rail transit systems;

- Increased precipitation may reduce road and transit system capacity and reliability directly and through an induced frequency of accidents.

- Transit system ridership may be affected by either heat or precipitation.

- Greater variability of precipitation may increase the frequency of disruptive weather events for which transportation agencies are unprepared, or alternatively, increase maintenance costs by requiring preparations for a greater range of low frequency events.

- Reduced snowfall may improve system reliability and reduce urban maintenance budgets.

- For coastal cities, increased flooding from relative sea level rise and storm surge can interdict or damage road and transit infrastructure as well as force mass evacuations.

All of these phenomena affect urban transportation systems today. The Texas Transportation Institute estimated the annual economic cost of traffic congestion in 2010 (including freight) at $100 billion.[86] The Federal Highway Administration, synthesizing multiple studies, estimated that current weather conditions accounted for about 15 percent of national congestion.[87] Climate change impacts will manifest themselves as progressive changes in frequency and severity of these events. Further, climate impacts on urban transportation systems are inherently interactive and non-linear.

Climate impacts can interact with one another, and effects on one mode can have consequences for other modes. A storm of sufficient magnitude to induce flooding may close individual roads or bridges. However, the associated precipitation may also directly reduce road speeds and hence road capacity, and considerably increase the risk of accidents, thus further reducing road capacity.

The existence of multiple travel modes can also produce interacting effects. When transit and road failures are uncorrelated, a failure on one mode can potentially be ameliorated by travelers shifting to the unaffected mode, reducing total delay, but increasing congestion on the unaffected mode. On the other hand, if failures are correlated, or a single failure (say a flooded road or bridge) affects both automobile and transit travel, then the effects are multiplied, and would be underestimated by measures on delay on a single mode.

Interacting effects are particularly important because congestion costs are non-linear.[88] Putting extra traffic onto an empty road has negligible effects. Adding traffic to an already congested road has disproportionate effects that increase as a function of the prior level of congestion. The economic cost of a particular congestion episode is primarily a function of the number of people and vehicles involved, the duration of delay, and the economic cost of delay, generally represented by the value of driver's time, the economic cost of freight delay, and the fuel cost of congestion. Hence the scale of future effects is inevitably dependent on the underlying levels of baseline congestion, and the timing and location of effects. A late-night weekend flood incident in rural Montana will probably have much lower economic consequences than a weekday afternoon rush hour incident in an already-congested major city.

Frequency of incidents matter as well. The Boston and Portland studies described above found that major flooding incidents that significantly affected transportation were primarily a function of low frequency events: typically 100-year floods. Even if a 100-year flood becomes a 30-year flood, it is still a rather infrequent event in terms of the economic costs imposed. As noted above, even ordinary storms can induce non-linear congestion effects at susceptible times and places, and the impact of increasing numbers and intensity of higher frequency small storms have not been studied.

Duration is also important. When climate effects are modeled as temporary interruptions of service, the costs occur over a period of a day or two. However, when infrastructure is damaged or destroyed, congestion effects can be spread out over a period of months or even years while repairs are made, even when alternative routes are available. The State of Minnesota estimated the economic cost to road users of the loss of the heavily traveled (140,000 average daily vehicle trips) I-35W bridge in Minneapolis, which failed in 2007, at $0.4 million per day, while a later independent estimate of the cost at $0.07-$0.2 million per day.[89] The replacement bridge was built in eleven months under a $234 million contract, not including a substantial bonus for early completion.[90] This example illustrates that the cost of damaged or destroyed infrastructure takes two forms: the cost of repair or replacement, and the potentially large economic losses incurred from loss of service.

The Portland and Boston studies also illustrate the importance of redundancy. If there are multiple bridges across a river, and one bridge is closed, traffic can route around the blockage. If there is a single causeway linking a barrier island to the mainland, the causeway will be critical to the welfare of the island population. The availability or absence of redundancy can have a large effect on the consequences associated with the closure of any particular infrastructure element.

Some trips are more important than others. Delays for emergency service vehicles may endanger lives and property. Every community contains vulnerable populations that are directly or indirectly dependent on transportation systems for their health. In every community there will be people who need access to dialysis, insulin, pacemaker batteries, oxygen tanks, and other drugs to survive. In addition, populations that need special care, such as hospital patients or nursing home populations are dependent are on transportation access for caregivers and supplies. Major failures of urban transportation systems can endanger the lives of vulnerable populations.

There is insufficient information at present to develop a reliable assessment of the magnitude if systemic risks to urban transportation associated with climate change. However, the available evidence suggests that urban transportation systems are at risk from a range of climate change impacts, and that the available studies do not span the range of potential impacts and consequences. The available evidence suggests that climate effects will, in part, be a non-linear function of pre-existing system capacity. Existing congestion loss estimates do, however, give some general sense of scale: incrementally worse weather ought to produce at a minimum, incremental worsening of national congestion costs.

D. **Ocean Shipping**

Ports. If the freight projections discussed in Chapter II are generally correct, the U.S. economy will become more trade-oriented in the coming years, which suggests increasing economic importance for maritime trade, and increasing volumes of cargo passing through U.S. ports.

Ports are likely to be affected by climate change.[91] Inevitably, ports are at the water's edge, with access to deep water and an elevation not much higher than the adjacent waterway. Many ports require large, flat, hard-surfaced yard areas for cargo storage. Ports are thus potentially vulnerable to relative sea level rise, storm surge, and flooding. To prevent flooding, ports are equipped with engineered storm water management systems that have some maximum designed capacity. Severe weather, including high winds and seas can interrupt loading and unloading operations. Particularly severe weather can force merchant ships to wait offshore. However, the definition of an extreme weather event that interrupts shipping is different and may be more severe than an extreme event that interrupts aviation. Both definitions may differ from the extreme event of a climatologist.

For ports at high latitudes, and on the Great Lakes, reduced icing may reduce operating costs and increase the length of the shipping season. Relative sea level rise may reduce dredging costs. However, depending on local conditions, siltation from increased storm water runoff may require increased dredging. Another consequence of relative sea level rise that may be of importance in particular locations is a reduction in effective bridge heights. Finally, in order to operate, ports require utility services, and viable land side connections for freight movements.

Generally, climate impacts are likely to manifest themselves as possible damage to facilities, loss of stored cargoes, possible effects on dredging, and changes in weather-induced port delays. As in other modes, the economic consequences of delay are a non-linear function of existing port capacity utilization and congestion.

At the national level, the consequences of port damage or delay would depend on the overall economic importance of the impaired port, the frequency of a loss or delay-creating event, the duration of the outage, and the availability of ready alternatives. For container traffic, the three busiest ports in the United States in 2010 were Long Beach, Los Angeles, and New York. These three ports handled almost half of U.S. container traffic.[92] In 2011, Long Beach handled some $62 billion in exports and imports, Los Angeles $53 billion, and New York, $44 billion.[93] Merchandise flows through these ports at rates in excess of $100 million per day, which gives some insight into the possible value of the cargo at-risk in the ports and the potential cost of delay. The situation on the West Coast is of particular interest because there are only five major container ports: Seattle, Tacoma, Oakland, Los Angeles, and Long Beach. Los Angeles and Long Beach are situated very close to each other, so risks to these two ports may be correlated.

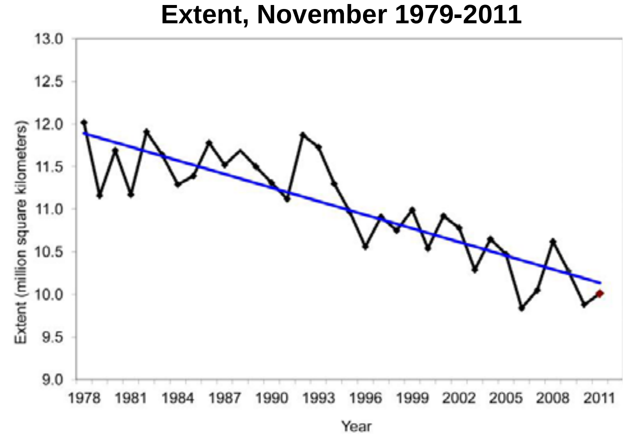
In addition to container ports, there are also ports specialized for handling particular cargo. Norfolk and Baltimore, for example, handled more than half of U.S. coal exports in the first nine months of 2011.[94] Grain elevators concentrated between New Orleans and Baton Rouge are vital to U.S. agricultural exports, while the Louisiana Offshore Oil Port is vital to crude oil imports. Both of these facilities are discussed in later sections of this chapter.

That some U.S. ports will be potentially affected by relative sea level and precipitation-induced flooding seems probable, especially on the Gulf Coast. While the risk seems likely, it appears that it will unfold slowly, creating time for cost-effective adaptation action. Given this, the prospect for national-scale, as opposed to local or regional consequences from damage or delay at ports seems relatively less likely. However, such a conclusion would be more firmly held if it were based on a port-by-port examination of specific risks.

Arctic Shipping. Historical records of the extent of Arctic ice indicate that the size of the Arctic ice cap has been declining for at least four decades.[95] Systematic observations of the extent and thickness of sea ice in the polar Arctic since the late 1970s show a steady decline in the extent of ice cover (Figure 10).[96]

With the shrinkage of summer ice, the Northwest Passage, a network of normally ice-choked bays and sounds connecting

Figure 10. Average Monthly Arctic Sea Ice Extent, November 1979-2011



Source: National Snow & Ice Data Center

the Atlantic Ocean with the Pacific via Greenland and the Bering Strait, has begun opening for short periods during the summer.

Climate modeling undertaken during 2006-2008 indicate that this trend will continue. Some models indicate that that the Arctic Ocean may be briefly entirely free of ice in the summer by 2100; one model suggests an ice-free period as early as 2050. No model suggests that the Arctic will be ice-free during the winter through 2100.[97]

There has been considerable discussion of the prospects for the commercialization of the Northwest Passage, which would open up a shipping short cut between Europe and Asia. However, the 2009 Arctic Marine Shipping Assessment was generally skeptical about near-term prospects for increased shipping through the Northwest Passage and the Northern Sea Route. The authors suggest that even if the Passage is open for a few weeks in the summer, it will still be closed most of the year, though the season will gradually become longer as the century progresses. For safety and insurance reasons, only specially-built Polar Class vessels with hulls strengthened against ice can be used, even during the summer season. High levels of natural variability in ice cover make the length of the season in any particular year difficult to predict. The quality of bathymetry (water depth soundings) in the high Arctic is generally poor, navigation aids mostly non-existent, and search-and-rescue and commercial salvage capacity distant. In addition, neither the United States nor Canadian governments have a sufficient number of icebreakers at present to support significant traffic through the Northwest Passage.

The Assessment concludes that significant traffic through the Northwest Passage before 2020 is very unlikely. However, the authors point out that “new ice” that is less than one year old is generally much thinner and structurally weaker than “old ice” that has survived at least one freeze/thaw cycle. As the permanent Arctic ice sheet shrinks, ever larger areas will be amenable to ice-breaking, even in the winter. The absence of suitable bathymetry, ice breakers, navigation aids, and search-and-rescue can all be remedied with time and sufficient incentive. The fundamental problem is the requirement for special ships for use during a short and uncertain season is likely to be commercially unattractive for shipping on a transformational scale, though increased transits by ecotourism cruise ships or a few specialized vessels are probable.

The authors point out that the main stimulus to Arctic shipping, if there is one, will probably not be the Northwest Passage, but the future exploration of the high Arctic for petroleum or mineral resources. Increased activity would require the construction of the necessary Polar-class vessels and stimulate the development of the required infrastructure. This may, in time, create conditions under which more through traffic becomes commercially feasible.

The probability of an ice-free Northwest Passage opening routinely during the summer months and a clearable passage in the winter months is high, though the date at which the Passage becomes consistently clear is scenario dependent. However, the national-scale economic consequences will likely be minor.

E. **Great Lakes Shipping**

The Great Lakes are a major transportation artery for U.S. domestic and foreign commerce. In 2009, some 109 million short tons of cargo were shipped through U.S. ports on the Great Lakes, about two-thirds of which (by weight) was "crude materials," notably iron ore. About a third of the Great Lakes trade is foreign, mostly destined to or from Canada.[98] Industry data from the Great Lakes Shipping Association indicate that significantly higher tonnages were shipped in 2010 and year-to-date 2011.[99] Shipments through U.S. ports account for only about half of the traffic on the Great Lakes, with Canadian shipments accounting for the other half.[100]

The Great Lakes are subject to complex climate change effects. The warming climate is gradually reducing the extent of annual ice cover, and promotes evapotranspiration. The lakes are recharged by annual precipitation, which has been relatively high in recent years. The water level in the lakes is subject to a regular seasonal cycle, and can also be affected by storm surge and other weather events. Beyond these short-term events, water levels are affected by multiple factors, notably the long-term balance between evapotranspiration and regional precipitation. There is thus considerable natural variability in lake levels, independently of climate change effects (Figure 11).

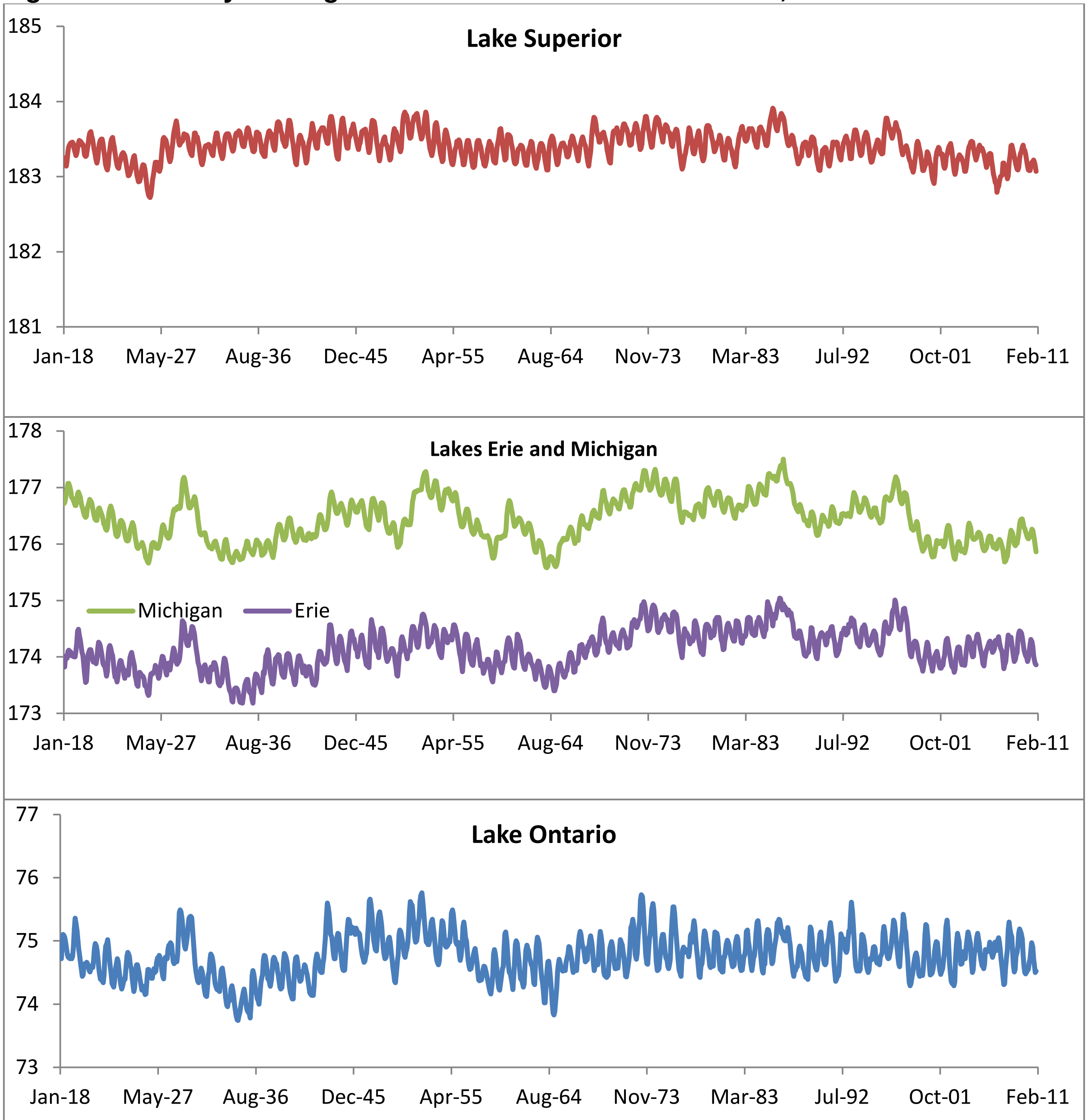
The primary impacts on transportation systems in the Great Lakes are:

Winter freezing. The shipping locks that connect the lakes freeze over in the winter, bringing most maritime activity to a halt from December through February. The Soo Locks, connecting Lake Superior with the lower lakes, are closed from January 15 to March 25 every year, with icebreakers used as necessary to compensate for fluctuations in the extent of icing. The locks on the St. Lawrence Seaway are opened or closed according to ice conditions, but typically remain closed from late December through late March. In recent years, there has been a gradual extension of the shipping season for the St. Lawrence Seaway: from 1982 to 1986, the Seaway was open an average of 269 days; from 2002-2006, the average season had increased to 279 days.[101] The Soo Locks operated year-round (using icebreakers) from 1974-1979.

With a warming climate and reduced ice cover on the lakes, it would be reasonable to expect a gradual lengthening of the shipping season, as the locks defrost earlier. In principle, this should reduce shipping costs since the same ships, ports, and facilities can be operated at a higher utilization rate. Shippers' production costs ought to decline as well, since stockpiling of cargos can be reduced.

The benefits of reduced icing can be distributed in varying ways. The U.S. and Canadian Governments can reduce icebreaking services while holding the season constant. Or, icebreaking can be held constant, and the shipping season expanded. However, the maximum gain from a longer season is probably modest, since the winter season is generally used for maintenance of the locks. The Soo Locks, for example, would be out-of-service for one month per year under current maintenance schedules, limiting the maximum gain from reduced icing to about five weeks, or about 12 percent of the available time.[102] This gain would then be distributed in unpredictable ways across the US and Canadian Coast Guards, the lock operators, ship owners, and shippers.

Figure 11.Monthly Average Water Levels in the Great Lakes, 1918-2010



Source: US Army Corps of Engneers, Detroit District
:http://www.lre.usace.army.mil/greatlakes/hh/greatlakeswaterlevels/historicdata/

Declining water levels. Secondly, declining water levels reduce the maximum draft of ports and particularly of locks. When water levels decline, large cargo carriers (particularly ore carriers) must reduce their draft by limiting the weight of their cargo. A recent *New York Times* article suggested that one inch of reduced water level reduced the capacity of the Great Lakes fleet by 8,000 tons.[103] Since the aggregate carrying capacity of the Great Lakes fleet is about 2 million tons, the percentage loss of capacity per inch of water level is about 0.4 percent.[104] Higher levels would increase the capacity of Great Lakes fleet. Since water levels naturally vary by season and through short-run precipitation patterns, the exact capacity of each ship depends on conditions at the time of voyage.

Predicting Great Lakes water levels in the face of climate change is difficult, since average water levels are the product of multiple regional-scale climate effects, including air and water temperatures, precipitation patterns, and ice cover. In addition, water levels are managed to a degree by the U.S. Army Corps of Engineers and the International Joint Commission Management Boards, and there are the usual uncertainties about future emissions, climate sensitivity, and human development patterns.

However, projections of future Great Lakes water levels have been developed based on several IPCC emissions scenarios and runs from a battery of Global Circulation Models (Table 3).[105]

This analysis suggests that while either a decline or increase in water levels is possible, a decline is more probable than an increase, and the expected magnitude of a decline (if one eventuates) is likely to be greater than any expected increase. There is little difference between scenarios through 2050. By 2080, though, both the magnitude and probability of a decline in lake levels scales with global emissions, so higher emissions make a decline more probable and the scale of the decline larger.

Table 3. Changes in Lake Michigan Water Levels, 2020, 2050, 2080
Meters Above/Below Datum)

Year & IPCC Scenario	Frequency of Observed Value in Meters Less Than (Percentile Rank)				
	5	25	50	75	95
B1					
2020	-0.6	-0.34	-0.18	0.02	0.28
2050	-0.79	-0.42	-0.23	-0.06	0.15
2080	-0.87	-0.51	-0.25	0.01	0.31
A2					
2020	-0.63	-0.33	-0.18	0.01	0.2
2050	-0.94	-0.52	-0.23	-0.02	0.42
2080	-1.81	-0.76	-0.41	-0.13	0.88

Source: James Angel and Kenneth Kunkel, "The Response of Great Lakes Water Levels to Future Climate Scenarios with an Emphasis on Lake Michigan-Huron," *Journal of Great Lakes Research Volume* 36 (2010), pp. 55.

If water levels change, there will be economic and operational consequences for shipping. While actually measuring economic consequences 50 or 80 years into an uncertain future present almost insurmountable difficulties, it is possible to use current information to gain some insight into the possible magnitude of such economic costs. Millerd (2011) estimated, based on simulation modeling of shipping movements in the recent past, a 5 percent increase in vessel operating cost based on a relatively small climate change, such as might be encountered in 2030, up to a 22 percent increase in operating costs based upon a doubling of atmospheric carbon dioxide, such as might be encountered circa 2070 under the IPCC A2 scenario.[106]

An alternative approach is consider the climate effect in terms of a relatively straightforward adaption approach: dredging. In recent years, there has been a lively debate on the desirable extent of dredging in the Great Lakes, since locks and harbor are prone to silting. The maritime industry has argued that the Army Corps of Engineers should be doing more dredging, since silting of harbors and locks, by reducing maximum draft, requires ships to reduce cargos.[107] The Corps, in turn, has attempted to calculate the economic cost of silting, as an input to determining how much dredging they ought to be doing.[108] The Corps' analysis of the costs of silting can be used as a rough proxy for the annual cost of falling water levels (Table 4).

Table 4. **Increased Cost of Reduced Great Lakes Water Levels: 2020, 2050, 2080**
(Million 2005 Dollars per Year)

Year & IPCC Scenario	Frequency of Observed Cost Greater Than (Percentile Rank)				
	5	25	50	75	95
B1					
2020	$125	$49	$17	($0)	($35
2050	$197	$69	$26	$3	($13
2080	$231	$95	$29	($0)	($42
A2					
2020	$135	$46	$17	($0)	($20
2050	$262	$99	$26	$0	($69
2080	$775	$185	$67	$10	($23

Source: Calculations based on: James Angel and Kenneth Kunkel, "The Response of Great Lakes Water Levels to Future Climate Scenarios with an Emphasis on Lake Michigan-Huron," *Journal of Great Lakes Research Volume* 36 (2010), pp. 55 and Jon Brown, *Great Lakes Dredging Evaluation*, (US Army Corps of Engineers, Buffalo District), Presentation to Inland Nav CoP Workshop, 20 Sept 2007.

The computations on which Table 4 are based are based on numerous assumptions and should be treated with caution, but they do serve to provide a first approximation of what the cost of falling water levels to U.S. shipping. The table assumes that the nature and composition of waterborne commerce on the lakes in 2020, 2050, and 2080 about the same as they were in 2005. Since Canadian shipping accounts for about half of the Great Lakes trade, the economic cost to both countries is probably about double the amounts shown on the table. While, in general, one would expect the Great Lakes trade to increase with a growing economy and population, in practice marine shipping on the Great Lakes is dominated by iron ore, coal, and grain, so the overall level of shipping in determined by the state of steel-making and coal-fired power generation in the Great Lakes, and secondarily by agricultural product flows.

The silting debate also generated a lengthy list of potential silting remediation actions, which double as potential adaptation actions if the water levels of the Great Lakes decline. These include additional dredging, shifting cargos to deeper water ports, engineering changes to the locks, and different designs for ships.

There are, however, significant issues with deepening channels. Many harbors and channels contain appreciable quantities of PCBs and other contaminants entrained in the silt, which would be potentially re-released in the event of extensive dredging. Some channels (Detroit River and

Welland Canal) have limestone bottoms, which would require blasting to maintain water levels. Deepening channels may affect water flows between the lakes, unless mitigated.[109]

Extreme weather events. Extreme weather events will periodically affect navigation on the Great Lakes, directly through forcing delays in vessel loading and changes in shipping movements, and indirectly by creating temporary changes and oscillations in water levels.

One study on extreme weather events indicated that there has been a statistically significant increase in the incidence of strong cyclones in the Great Lakes region over the period of 1990-1999.[110] If this trend is accelerated by climate change, then extreme weather events will periodically affect navigation on the Great Lakes, directly through forcing delays in vessel loading and changes in shipping movements, and indirectly by creating temporary changes and oscillations in water levels.

An appreciable decline in the Great Lakes appears likely in the event of a high emissions scenario, possible in the event of a low emissions scenario. Or, alternatively, a decline in the Lake water levels will occur earlier in a high emissions scenario, later in a low emissions scenario. The net effect on shipping appears to be manageable, and potentially subject to cost-effective adaptation action. Therefore, net effects are likely to be low, though the timing of the consequence is scenario-dependent.

F. Climate Impacts on Agricultural Product Flows

Introduction. Agriculture is perhaps one of the most important and well-studied sectors that will be affected by climate change. In crop year 2009/2010, total US supply of corn, soybeans, and wheat accounted for 39, 31, and 9 percent of the world's supply.[111] In recent years, there has been a gradual northern shift of crop production. Reilly (2003) constructed the geographic centroid of maize and soybean production and found that it shifted northwards by 120 miles from 1870 to 1990.[112]

The United States maintains a large and complex inland maritime transportation system, spanning the Missouri, Ohio, and Mississippi Rivers. Table 5 illustrates freight flows on these major river systems in 2009.

Table 5. Volume of Cargo Transported on Main River Systems, 2009 (Million Short Tons)

River System	Total Tonnage	Food & Farm Products	Coal
Missouri	5.1	0.1	--
Ohio	229.5	14.7	136.3
Upper Mississippi	62.2	30.2	5.9
All Mississippi	447.7	143.9	51.0
Mississippi + Tributaries	622.1	145.0	171.5

Source: U.S. Army Corps of Engineers, *Waterborne Commerce of the United States*, CY 2009 Part 2 (December 2010).

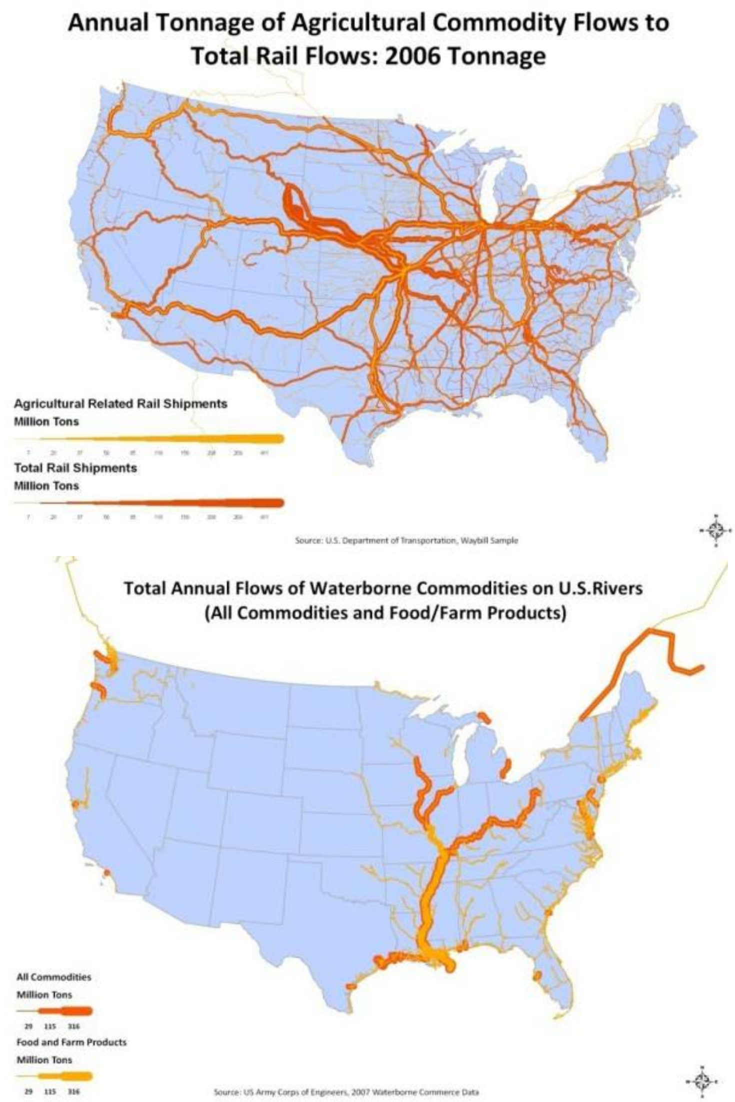
An efficient, low-cost system of transportation is an important contributor to the success of American agriculture. Barges, railroads, and trucks facilitate a highly competitive market that bridges the gap between US grain producers, domestic and foreign consumers. Agriculture is a major user of freight transportation systems, accounting for 22 percent of all tons and 31 percent of all ton-miles transported via all modes in 2007.[113]

Figure 12 shows the spatial pattern of rail and waterborne flows of agricultural products. This pattern will likely be affected by climate change.

This waterborne system includes numerous locks, dams, and pools, which serve multiple purposes, including flood control, navigation, and irrigation. The management of ever-varying water flows for these multiple purposes presents the system operators (primarily the Army Corps of Engineers) with an extraordinarily complex management problem. Climate change can only increase the complexity of this situation.

The Upper Mississippi and Missouri River systems are subject to extensive management, based on planned water releases from a network of dams. The Corps attempts to provide sufficient water to provide for a 9-foot water depth along the navigable portion of these rivers for the length of the navigation season, typically late March through late December. During the winter, the rivers ice up, halting navigation, and the locks are taken out of service for maintenance.

Figure 12. Annual Rail & Maritime Flows of Farm Products vs. All Products, 2007



Source: USDA/ USDOT, *Study of Rural Transportation Issues* (April 2010), pp. 21-22. (Chapter 2). Shttp://www.ams.usda.gov/AMSv1.0/ruraltransportationstudy. Data from USACE, *Waterborne Commerce of the United States, 2007.*

In years when more water is available, the Corps can increase dam releases for navigation, increasing river depth and permitting the transit of more deeply laden barges, which reduces transportation costs. However, the timing of increased water flows is also important. Earlier, more rapid spring snowmelt may have the perverse effect of increasing spring flooding while still producing lower water levels during the harvest season.

Transportation, Season Length, and Water Availability. In principle, a climate-change-induced shorter winter season ought to reduce the extent of icing on the Upper Mississippi and Missouri rivers, and permit a longer shipping season, which should also reduce transportation costs. However, the Corps faces competing demands for water releases, and may not always have sufficient water to support a longer shipping season. Or, the Corps may have to choose to allocate water between more shipping days with reduced water depth, or fewer days with greater water depth.[114] In any case, requirements for lock maintenance set a limit on the extension of the shipping season, even if ice and water availability are no longer constraints.

Thus, the impact of climate change on shipping conditions is closely tied to water availability, which in turn is a product of future precipitation patterns and resulting surface water flows, as well as alternative uses for available water. In general, though, the existence of net benefits from reduced freezing on waterborne transportation would require increased precipitation and/or water availability as well as reduced freezing. While reduced freezing seems likely, water availability is unclear, raising uncertainty about the outcome. It is also unclear whether a higher emissions scenario would increase or reduce regional water availability. However, the requirement for lock maintenance puts a ceiling on the extent of the benefit, leading to a low positive consequence.

Extreme weather events. On the other hand, increased frequency of extreme events presents significant challenges for riverine transportation. Droughts reduce water levels, and require that barges be more lightly laden, or, in some cases, block shipping altogether. Flooding events can halt river traffic, damage or destroy ports, locks, navigation aids, and even vessels, as well as create hazards to navigation in the form of sunken ships, new sand bars and floating debris. The build-up and collapse of ice dams can also damage individual bridges and locks in the absence of more general flooding. The linear nature of rivers means that a single damaged lock can halt enormous volumes of river traffic. A 2008 storm closed 18 locks for a total of 37 days: 1993 flooding closed the Mississippi River to navigation for two months.[115] Locks and ports are also vulnerable to flood events that interdict their landside connections or interrupt utility service.

Flooding also affects rail and freight traffic as well: roads and rail lines can be overtopped, bridges and culverts can be damaged. Flood events sufficient to cause prolonged closure of waterways are likely to affect rail and road traffic as well, multiplying the effects of waterway closures. Since the main East-West rail lines all cross the Mississippi, and many North-South lines cross the Ohio, the Missouri, or their many tributaries, flooding events can also halt rail traffic more generally.

There have been frequent large floods on the Mississippi in recent years, and there are a priori reasons for believing that increased precipitation and increased climate variability in the Midwest and Great Plains regions would increase the frequency of flooding on the Mississippi., However, it is not clear that the current state of regional climate analysis is sufficient to support a strong conclusion that climate change will cause increased flooding in the future. A recent study by Wuebbles et al (2008), based upon downscaled climate results from four IPCC climate scenarios linked to a hydrology model, suggests that winter and spring precipitation in the upper Mississippi will increase, with increased run-off into the Mississippi.[116] The National Climate Assessment scenario work, when completed, may offer a more definitive view.

The seasonal nature of agricultural production means that there are relatively better or worse times for shipping interruptions on the inland waterways. Barge rates on the Mississippi are lowest in March, and peak in October, at a level more than double the trough rate.[117] Significant transportation system failures, especially during the post-harvest peak shipping season can quickly ripple back to farm gate prices and forward to world commodity prices. Hurricanes Katrina and Rita, which briefly closed the lower Mississippi, sank or damaged more than 400 barges, and disrupted grain elevator operations, briefly caused barge rates to quadruple, raised export corn prices by $0.40 per bushel while farm prices dropped $0.20 per bushel.[118] [119]

Another potential effect of more frequent extreme weather events is loss of agricultural yield, both directly through crop loss and indirectly through increased variability in weather.[120] Reduced yield would reduce regional surpluses, and hence inter-regional transport of crops.

Increased climate variability may manifest itself in an increase in the frequency of both floods and droughts, with impacts on shipping in both directions. Thus, increases in climate variability and increases in extreme events may reduce the reliability of marine transportation systems and, in principle, increase risk and volatility of agricultural commodity prices. This, in turn, opens a path to estimating the economic cost of climate impacts, since historical information on river closures and commodity prices can be used to derive estimates of the potential cost of increased frequency of future floods and droughts.

Barge and rail systems provide alternative mechanisms for moving crops to market, and many of the grain elevators on the lower Mississippi also have rail connections, and crops can be also be moved to alternative ports. In 2007, some 65 million tons of cereal grains were shipped by water to Louisiana, while only 8 million tons traveled by rail.[121] While rail can help ameliorate small-scale or off-peak capacity limitations on the Mississippi, it seems unlikely that the rail system can fully replace the marine system in the event of a prolonged harvest-time outage. Events (such as flooding) that affect both rail and barge traffic would be particularly damaging.

The probability of more frequent extreme weather events appears to scale with increased severity of climate change. The consequence of extreme events is a function of their timing and frequency. If the increased frequency of extreme events is low, and they occur as part of the spring thaw, consequences are likely moderate. If the frequency is greater, and events occur during high usage periods, then consequences could be greater.

Changing agricultural commodity mix. One of the most important functions of the inland waterways is to deliver U.S. agricultural commodities to domestic and overseas markets, the latter via the Mississippi to export-oriented grain elevators in New Orleans. The 145 million short tons of food and farm products transported by water on the Mississippi and its tributaries in 2009 included 65 million tons of corn and 46 million tons of soy beans.[122] Some 72 million tons of food and farm products were "foreign shipments," presumably exports.

However, this vast commodity flow depends on the Midwest continuing to cultivate corn and soy beans, and a concomitant flow of agricultural exports. There are several mechanisms by which climate change could affect the transportation system:

Corn and soy bean yields are subject to complex interacting effects from climate change, including peak and average temperatures at various points in their growth cycle, water availability, and CO_2 fertilization. To a first approximation, climate change appears to reduce corn and soybean yields in the Midwest, at a probability, as assessed in 2008, of "possible to likely."[123] Accurate prediction of ex ante yields requires an accurate assessment of the relative strength of temperatures, temperature variability, and precipitation on a regional scale, which then has to be combined with crop modeling.

In turn, farmers can change crops, crop varieties, and cropping practices to reflect changing climactic conditions. Seed firms can develop new crop varieties that are suited to changing climatic conditions. Transportation systems will be affected by the net product of climate impacts as modified by farmer's adaptation actions.

Attavanich et al (2009) attempts to quantify the impacts on climate change on crop production and transportation flows.[124] This study uses four different changes in crop yields derived from simulated regional climate across the United States in 2050, using four different global circulation models, all based upon the IPCC's A2b (high emissions) scenario. The changes in crop yields are then applied to a national-scale agricultural production model (the Agricultural Supply Model). The results of the production model are applied to a transportation model (the International Grain Transportation Model.)

Given the range of uncertainties, the confidence to which one can attach to any particular outcome is low, but the results are instructive as an example of the sort of results that one might expect. Broadly, the Corn Belt moves north. The southern sections of wheat producing areas become the Northern section of corn-producing areas. The crop results are highly sensitive to projected regional climate: simulated 2050 production of all crops ranges from 92 to 118 percent of base (2007) production, while production of corn ranges from 83 to 109 percent of base production, and soy production from 92 to 101 percent of base. The shift in production generates large shifts in transportation flows (Table 6).

If corn production shifts northward, optimal transportation routes change as well. Less corn moves by barge and rail down the Mississippi, and more corn begins to move by rail to the Great Lakes and ports on the Pacific Northwest. Total corn exports also decline in three of the four cases. Soy bean patterns are model dependent: in one case, soy bean exports rise almost 50 percent, while in another case, they decline by a third, but without the obvious shift in the spatial pattern of exports. Shifts in the pattern of exports are mirrored by shifts in mode, with rail shipments rising, and barge shipments declining.

Table 6. Exports of Corn and Soybeans with Climate Change, 2050
(Thousand Metric Tons per Year)

Crop & Route	Baseline	MRI-CGCM2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Corn-Total	61,573	66,460	56,198	45,849	50,687
Via Pacific Northwest	12,418	18,974	21,163	14,093	20,727
Via Great Lakes	602	3,693	3,532	3,647	582
Via Lower Mississippi	37,550	33,132	17,189	21,484	20,667
Soybean-Total	29,042	43,465	31,881	21,911	30,588
Via Pacific Northwest	8,312	9,807	8,587	7,168	9,719
Via Great Lakes	616	1,805	1,517	2,180	843
Via Lower Mississippi	16,724	26,415	17,664	8,614	16,333

Source: Witsanu Attavanich, Bruce McCarl, S. Fuller, D. Vedenov, and Z. Ahmedov, "The Effect of Climate Change on Transportation Flows and Inland Waterways Due to Climate-Induced Shifts in Crop Production Patterns," presentation at Agricultural & Applied Economics 2011 Joint Annual Meeting, Pittsburg, PA, 24-26 July 2011.

While the Midwest and the Northern Plains will likely become warmer, the agricultural outcome seems exceptionally difficult to predict and the transportation outcome even more so. It is hard to assign a high probability to any particular outcome. The modeled consequences are interesting and regionally important, but do not appear to be particularly large at a national scale.

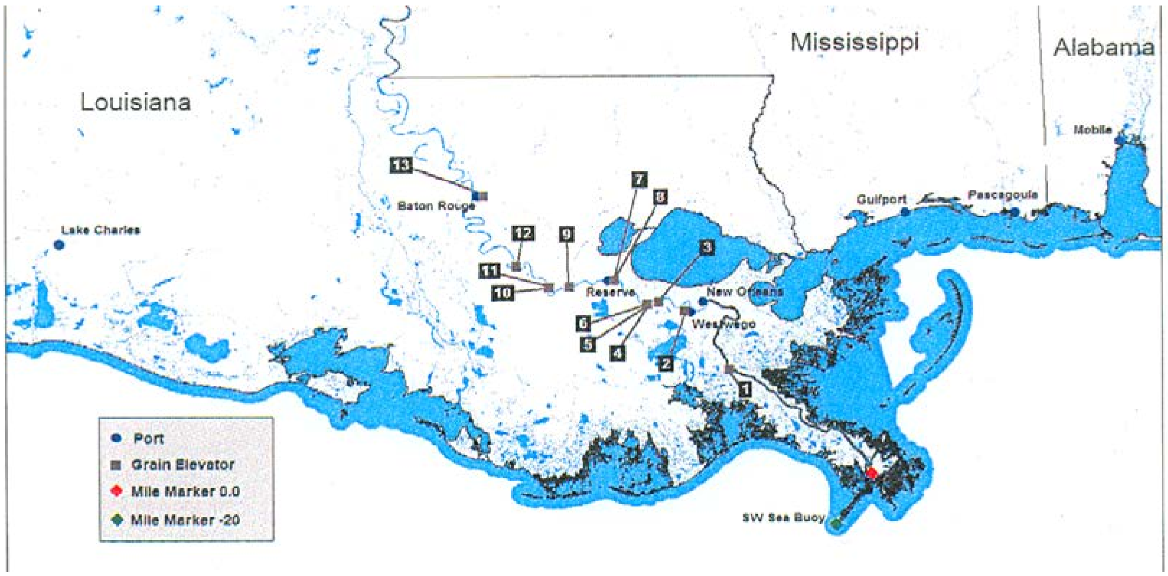
Freight shipments and the Gulf Coast. Gulf Coast ports are a key element in U.S. freight systems. In addition to petroleum production and refining, there is also a large concentration of petrochemical facilities, and a major rail line running just North of New Orleans. At New Orleans, the Intercoastal Waterway intersects with the Mississippi, providing two major avenues for shipment of bulk cargos. DOT's Gulf Coast Study has an extensive discussion of the implications of sea level rise and storm surge on freight systems.[125]

U.S. grain exports terminate in a small number of large grain elevators, where cargos are transshipped from barges and railcars into oceangoing bulk carriers. There are thirteen such elevators on the lower Mississippi, mostly between Baton Rouge and New Orleans (Figure 13).[126] In 2009, the U.S. exported some 161 million tons of "food and farm products" by sea, of which 71 million tons were exported from the ports on the lower Mississippi.[127] These facilities are subject to flood hazard, storm surge, and interruption of their landside connections.

The concentration of facilities in a small area implies a concentration of risk. An event that damages any single facility may put multiple facilities at risk. Similarly all of these facilities are dependent on both oceangoing shipping traffic and barge traffic moving on the Mississippi. Timing may be important, since utilization of these facilities is seasonal.

The climate risk to these facilities is a function of the interaction sea-level rise (probability high), increased intensity of hurricanes, and potential fresh water flooding. On the other hand, national consequences depend on simultaneous damage to multiple facilities during the summer/fall export season, which falls within the hurricane season. National consequences also depend on the frequency of a damaging event, as well as any adaptation action that may be taken. Overall, the probability of a multiple-elevator event seems medium-to-low, though the consequences should such an event occur after the harvest would be high.

Figure 13. Grain Elevators on the Lower Mississippi



Source: Randy Schnepf and Ralph Chite, *U.S. Agriculture After Hurricanes Katrina and Rita: Status and Issues* (Congressional Research Service, October 5, 2005), p. CRS-7.

Perishable Goods. Perishable goods require special handling to arrive at their destination in saleable conditions. Most, but not all perishable goods are foodstuffs, including live animals, meat, frozen foods, and fresh fruits and vegetables. They move by primarily by truck. Many perishables are transported in refrigerated vehicles, containers, or trailers. In 2007, the reported domestic truck trade in “live animals and fish” was 104 million tons, with a value of $134 billion. “Meat and seafood” shipments were 102 million tons, valued at $291 billion.[128]

Generally, a warmer climate places extra pressure on perishables. Live animals can die of heat stress, fruits and vegetables spoil, and refrigeration and insulation may not be adequate to the task. Further, perishables are particularly affected by both delay and declining reliability. An unplanned delay can lead to loss of perishables. If the reliability of freight systems declines, shippers will find it more difficult to ascertain whether or not a given cargo will arrive safely, which, inhibits trade and raises costs.

Perishable shipment practices can be improved. Current operating practice in the southern United States may move north. Freight operators can invest or innovate to restore reliability. However, given the high value of perishables, even a small percentage loss can have a large dollar value.

Higher temperatures are very likely: however, given the trucking industry’s practical experience shipping perishables in the southern United States, successful adaptation is probable. However, perishable losses in the event of unplanned delay or declining reliability may cause losses.

G. **Impacts on Aviation**

Commercial aviation in the United States is subject to multiple climate change effects.

Effects of rising air temperatures. FAA advisory circular 150/5325-4B describes the relationship between aircraft weight and thrust, runway length and aircraft class.[129] Virtually all commercial and most military aircraft in the United States are powered by gas turbine engines. Gas turbine performance is sensitive to air temperature and pressure (altitude). This sensitivity is derived from multiple aspects of engine design, but one important constraint is a limitation on combustor inlet pressure.[130] The limitation on combustor inlet pressure reduces the effective maximum thrust of jet engines at higher ambient temperatures. Limitations on maximum engine thrust reduce the effective excess thrust of jet aircraft, which, in turn reduces the safe (or rated) maximum allowable take-off weight for the aircraft.[131]

Reducing maximum allowable take-off weight reduces the maximum fuel load (and hence range) and/or maximum payload for a commercial aircraft. The aircraft performance penalty is specific to particular airframe/engine combinations and airports, and depends on a host of operational factors. Reduction in maximum thrust also causes aircraft to accelerate more slowly, so aircraft may also require a longer takeoff run to reach a given velocity, which may be a constraint at some airports. Twin engine aircraft have greater excess thrust than four engine aircraft,[132] so the constraint may more commonly manifest itself as a runway length constraint for four engine aircraft, and a gross takeoff weight constraint for twins.

Current climate projections suggest increasing numbers of days with temperatures exceeding 90°F throughout the United States. It is reasonable to expect that increasing numbers of commercial flights may potentially be affected by temperature-induced range or payload limitations. However, on many routes, the length of the trip doesn't require a full fuel load so maximum gross weight will not be a constraint. Flights departing when ambient temperatures are below 32° C (about 90°F) will be little affected.

Airlines, airports, and airframe manufacturers have multiple adaptation options. Airports that are constrained by short runways with a warming climate can lengthen runways.[133] Airlines may adapt by reducing payload, adjusting inputs to aircraft scheduling algorithms and amending their engine and airframe purchasing plans. Airframe manufacturers can add excess thrust or reduce the weight of future generations of aircraft. Engine manufacturers may be able to improve their designs to provide better hot-weather performance. Although none of these adaptations are free, the cost will likely be included in some combination of higher operating costs or marginally more expensive aircraft, and therefore may not be detectable.

Weather effects. Weather is currently a significant source of commercial flight delays, accounting for 37 percent of delayed flights and 39 percent of delay minutes between June 2003 and October 2011.[134] Both total delays and delays attributable to weather have declined over the past eight years. While some weather delays are caused by "extreme events," the bulk of weather delays emanate from the connected nature of the National Air Space System, where a weather event at one airport leads to delayed departures in other areas.[135]

Delays impose costs on airlines and the traveling public. Ball et al (2010) estimates the cost of aviation delays in 2010 at $32.9 billion.[136] About half of the costs are borne directly by the traveling public, about a fourth by airlines, with the balance distributed across the economy as a whole. The costs of current delay provide a basis for considering future costs of delays arising from changes in the frequency of weather events.

There is unlikely to be a simple correlation between an increased incidence of bad weather and increasing flight delay costs. Aviation congestion, like other forms of congestion is a complex, non-linear process. Bad weather often acts to reduce various kinds of capacity in the system, by delaying or cancelling arrivals and departures. When the system is congested, even small impairments have disproportionate consequences. Consequently, weather events are most influential when they take place during peak periods in areas where traffic is concentrated and capacity is limited.

More frequent extreme weather events as a result of climate variability may cause flight delays, and raise the prospective cost of inadequate system capacity.[137] However, the cost of climate impacts may be managed by some combination of more capacity, improved dissemination of accurate weather information within the national air space system, better short-term weather forecasts, and innovations in aircraft and airport operations.

Airport operations are also dependent on surrounding infrastructure, including electric power, jet fuel deliveries, and passenger or freight connections to surface transportation. Climate impacts on airport landside connections can also affect aviation.

Warmer temperatures may reduce snow accumulation and the need for de-icing, which would provide operational benefits to aviation. However, since climate change may also bring an increase in precipitation, these benefits may be offset. Precipitation and temperature change will vary greatly across the United States, so each region will face particular adaptation issues. Greater climate variability is difficult to manage, since it might require airports may to increase staff and dedicated equipment on hand to deal with an extended range of weather effects (for instance, ice storms), even if average temperatures are higher.

Sea level rise. Airports require enormous flat areas, which are extensively covered with impermeable concrete and asphalt. Some are at risk for flooding, and all have engineered systems for drainage and storm water management. These runoff containment systems, however, have a finite capacity. Since a large fraction of the U.S. population lives in coastal cities, many major U.S. airports have been built on reclaimed land close to sea level (Table 7).

Rising sea levels pose a challenge to airports and the drainage systems that protect them. Even modest sea level rise will elevate water tables, which raises the potential impacts from a rain event. Big storms can locally elevate water tables through rain and storm surge, while winds, tides, and storm surge can back up onshore run-off into bays and harbors. Airports can be protected by levies, and storm water management can be improved, but only by design and investment. Figure 14 and Figure 15 illustrate flooding scenarios developed for Boston and the San Francisco Bay for various levels of sea-level rise.

Table 7. Major Coastal Airports at Low Elevations

Airport Name	City & State Served	2010 Passengers (million)	Altitude Above Sea Level (feet)	Highest & Lowest Reported Tide (feet)	Historical Sea-Level Rise (feet/century)
Louis Armstrong	New Orleans, LA	4.07	4	16 – 0	3.03
Oakland International	Oakland, CA	4.65	6	13 – 1	0.66
Miami International	Miami, FL	16.75	8	15 – 9	0.78
Fort Lauderdale	Fort Lauderdale, FL	10.76	9	15 – 9	0.78
John F. Kennedy Int'l	New York, NY	23.11	13	12 – 0	0.91
San Francisco Int'l	San Francisco, CA	19.33	13	15 – 3	0.66
Lindberg San Diego	San Diego, CA	8.41	14	12 – 1	0.68
Reagan National	Washington, DC	8.76	15	16 – 0	1.04
Newark Liberty	Newark, NJ	16.52	18	14 – 1	1.28
Logan Boston	Boston, MA	13.59	19	19 – 0	0.86
La Guardia	New York, NY	11.93	22	13 – -1	0.91

SOURCE: Bureau of Transportation Statistics T-100 Market data. Historical sea level rise from National Oceanographic and Atmospheric Administration (NOAA), sea level trends online database. NOAA calculates the least squares trend line for about a century of data. Tides from observation station closest to the listed airport. Maximum/minimum water levels are the reported highest/lowest ever recorded for a particular station. See: http://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Figure 14. Boston Flooding at High Tide with 2.5-ft Sea Level Rise and 5-Ft Storm Surge

Source: Ellen Douglas, "Risk Management & Sea-Level Rise," Presentation 24 April 2011, http://boston.uli.org/ULI%20Committees/~/media/DC/Boston/Boston%20Docs/RiskManagementSlides.ashx

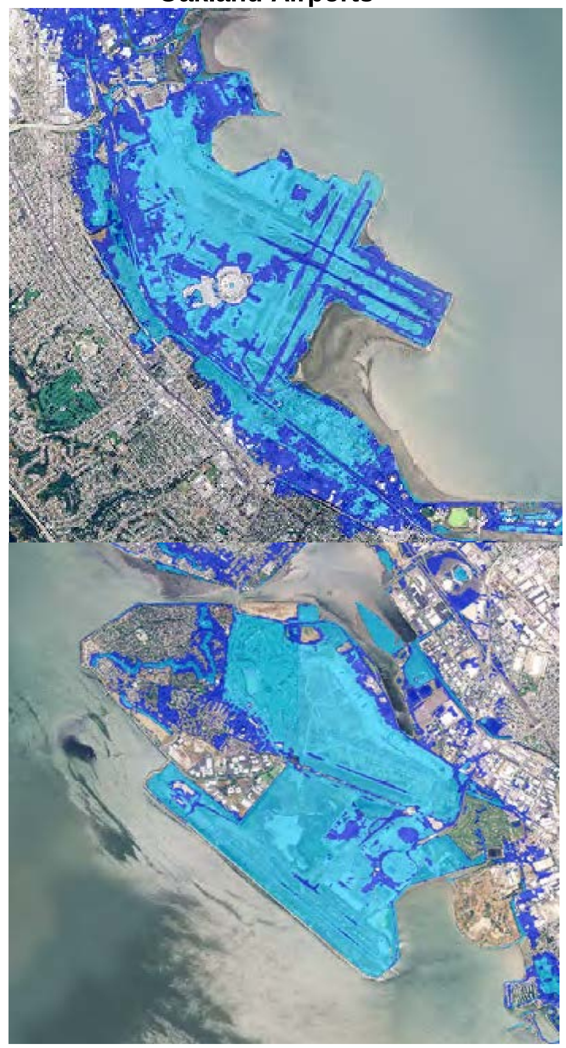
With the exception of New Orleans, major airports are not at risk for simple inundation based upon historical trends of sea level rise. However, recent studies suggest a substantial acceleration in global sea rise over the next century. The NCA anticipates a mean global sea-level rise of 1.4 meters (4.6 feet, or 54 inches) by 2100.[138]

Based on multiple factors such as local uplift or subsidence, sea-level rise may vary substantially from the mean global figure. based on multiple factors. Research on deriving local sea-level rise projections from global projections is underway.

Airports are also potentially subject to the risk of shoreline erosion. Shoreline erosion is the product of the interaction between climate, sea level changes, wave action, and local geology.[139] However, airports that are sheltered from direct wave action will usually be at lower risk for erosion.

Flood events that affect airports in one part of the country will likely cause delays in other parts of the country. Airports are routinely subject to temporary closures for weather or other reasons. Multiple simultaneous closures of adjacent airports would probably have a more significant impact on system performance than closures of unrelated airports.

Figure 15. Flooding With 16- & 55-In Sea-Level Rise at San Francisco & Oakland Airports



Note: Assumes sea-level rise plus highest monthly tide 1996-2007 (which would include surge/flooding). Does not include existing shoreline protection.
Source: San Francisco Bay Conservation & Development Commission, *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*, (Draft Staff Report), September 23, 2011.
http://www.bcdc.ca.gov/BPA/LivingWithRisingBay.pdf

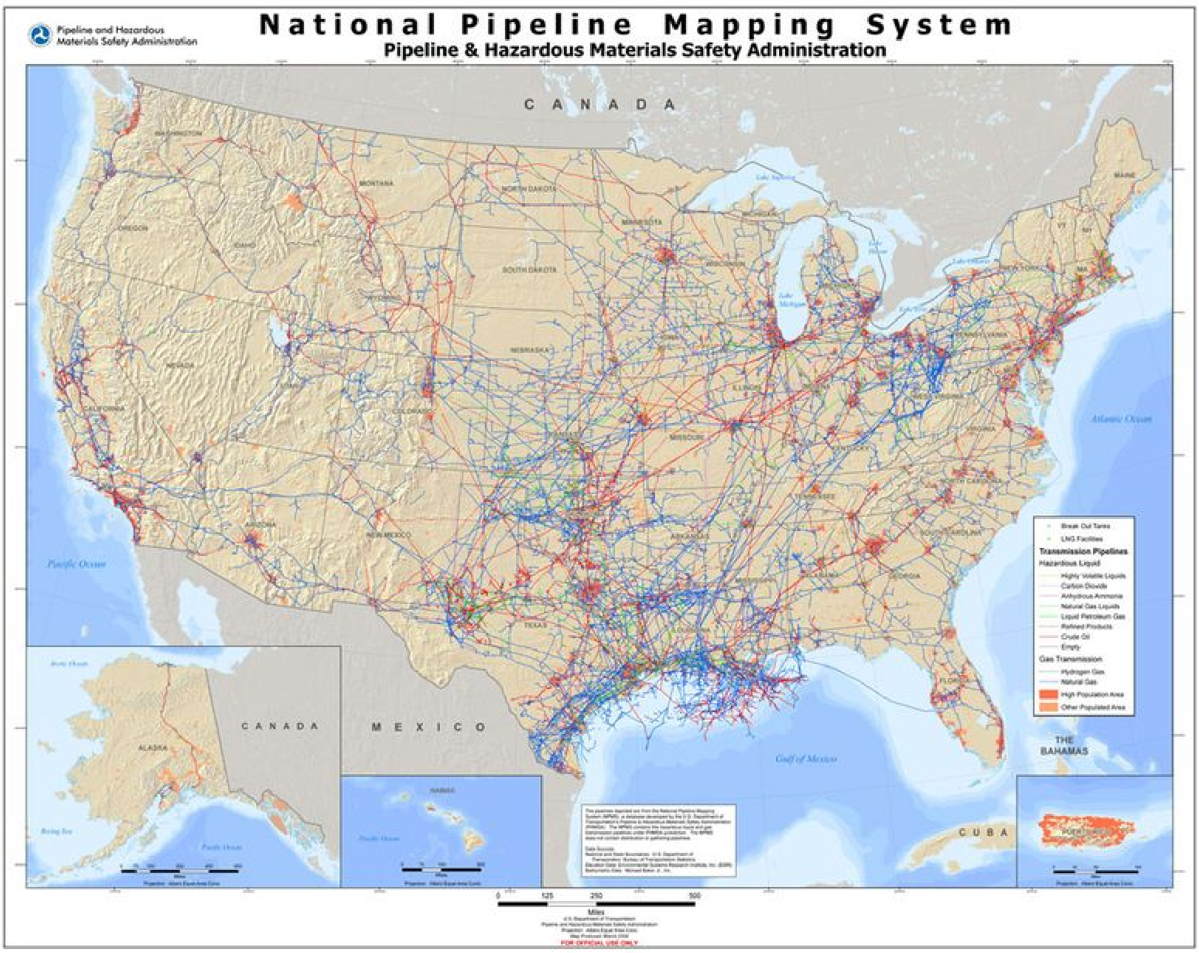
While the most important role of airports is to move people, air cargo also plays an important role in moving high-value products, particularly U.S. exports. The air cargo export trade is concentrated in a relatively small number of airports: Kennedy Airport shipped $96 billion in exports in 2011, San Francisco Airport shipped $26 billion, and New Orleans shipped $24 billion.[140] While air cargo shipments can be quickly diverted, these figures give some insight into the value of cargo awaiting shipment that might be at risk in the event of an unanticipated flood event.

As in other cases, the probability that major airports will eventually be subject to climate impacts from flood and storm surge in a high emissions scenario is dependent on the probability of the projected sea level rise actually occurring. If the world experiences a 2100 global sea level rise of 1.4 meters, the probability of some major U.S. airports being affected is high. The probability is lower for low emissions scenario. However, it is also likely that airport operators will take adaptation action in some form as the scale of the actual threat becomes clearer.

H. **Petroleum Infrastructure and Transportation**

At present, petroleum accounts for some 96 percent of transportation sector energy consumption, and the transportation sector is consequently dependent on continuous deliveries of refined petroleum products in order to operate.[141] A complex specialized web of crude oil and petroleum products pipelines deliver petroleum from domestic oil fields and import terminals to refineries, and from refineries to consumption centers (Figure 16). In addition, petroleum products and sometimes crude oil are transported by rail and barge. Corn-based ethanol, which is largely blended with gasoline, is largely shipped by rail.

Figure 16. U.S. Petroleum and Natural Gas Pipelines



This petroleum transportation system is generally robust and functions well. However, if climate change affects petroleum refining or transportation, these impacts could have a second-order impact on the transportation system. The principal climate risk to this system lies in the concentration of petroleum refining and import facilities along the Gulf Coast, and the extreme sensitivity of the transportation system to interruptions in supplies.

Among the key pieces of infrastructure is the Louisiana Offshore Oil Port (LOOP). The LOOP is the only deep water port in the United States suitable for unloading the largest super-tankers. Typical throughput is about 1.2 million barrels per day, or about 6 percent of U.S. petroleum consumption. The facility comprises three floating single-point mooring buoys, connected to an onshore terminal with tank storage and connections to crude oil pipelines linked to multiple refineries. In addition, several underground storage caverns of the Strategic Petroleum Reserve are located nearby, and the nexus of crude oil pipelines is itself an important element of the domestic crude oil market in the United States. The LOOP far out on the Mississippi delta, and is subject to risks from hurricanes, flooding, sea-level rise, and shoreline erosion. The facilities have weathered several major hurricanes in recent years with minimal damage and only brief suspensions of operations, which suggests that the facility is well-hardened. However, a prolonged shutdown of the LOOP or the associated pipeline interconnections would materially raise the cost and price of petroleum products in the United States, and would cause significant operational inconvenience. From a national economic point-of-view, it is important that the LOOP continues to operate reliably in the face of foreseeable risks.

Some 47 percent of U.S. crude oil distillation capacity is located in just three states: Texas, Louisiana, and Mississippi.[142] Most of this capacity is located close to the coast or a navigable waterway, and at elevations of less than 25 feet. Even within these states, most refining capacity is concentrated in eight locations: Corpus Christi, Texas City, the Houston Ship Channel, Beaumont/Port Arthur, Lake Charles, New Orleans, Baton Rouge, and Pascagoula, MS. All of these areas are subject to significant hurricane risk, and some are at risk for sea level rise/subsidence, shoreline erosion, and possibly salt water intrusion. Salt water intrusion may present operational difficulties both for process water quality and also corrosion of pipelines that were not designed to be exposed to saline ground water.

Generally, refineries have weathered recent hurricanes with relatively little damage, in part due to significant investment in levees and other protective works. However, the experience of Hurricane Katrina suggests that if a refinery does flood, it will be put out of operation for a prolonged period.[143]

The effects of unplanned refinery shut downs are difficult to assess, as they tend to depend on the availability of global excess refining capacity. After Hurricane Katrina, excess refining capacity in Europe was available to substitute for damaged U.S. refineries, which limited the scale of the impact on U.S. petroleum consumers, including the transportation sector. If excess refining capacity is not available, then product prices will rise until the global shortage of products is suppressed.

In principle, refineries could be relocated to more secure venues. In practice, no new refinery has been constructed on a new site in decades. Suitable sites, large tracts of unoccupied level ground, preferably adjacent to the coast with access to pipeline, marine, and rail transportation links, would be difficult to find. This suggests that existing refinery sites are likely to be protected.

Pipeline infrastructure is also subject to specific climate risks. Generally, pipelines are buried, and river crossings carefully protected, so precipitation, flooding and scour are unlikely to be common problems. There may, however, be situations where pipelines designed to resist fresh water corrosion may be subjected to salt water due to coastal salt water intrusion. Such pipelines might require premature repair or replacement.

The all-weather reliability of pipeline systems is one of the advantages of this technology. However, pumping stations (for liquids) and compressor stations (for gases) are essential surface facilities that are subject to the usual risks of any surface infrastructure, in addition to which they require reliable energy supplies. Service interruptions of major pipelines due to hurricanes have generally been due to temporary evacuation of personnel and interruption of electricity service. As in the case of the LOOP, there are pipelines and pipeline systems of national importance that should run reliably in the face of foreseeable risk.

Given the location of petroleum infrastructure combined with the near certainty of continuing subsidence in the Gulf, and considering the probability of continuing sea-level rise and the near certainty that more large hurricanes will arrive on the shores of the Gulf over the next century, the probability of a significant loss of refining capacity is very high. On the other hand, the risks are well known, and the assets at risk are valuable, and the cost of interruption is high and well understood. The probability of substantial (even if expensive) adaptation action also should be high.

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[133] The Gulf Coast study has a lengthy discussion of the interaction between runway length and aircraft performance. CCSP (2008). *The Gulf Coast Study, Phase I*, pp. 4-30 – 4-36.

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V. Effects of Declining U.S. Emissions on Transportation

A. **Overview**

U.S. anthropogenic carbon dioxide emissions in 2009 were about 5.5 billion metric tons.[144] The Energy Information Administration expects very slow growth of emissions (about 5.5 percent in through 2035) in its reference case. The A2 *global* emissions scenario is consistent with a wide range of *U.S.* emissions futures, from rapid growth to slow decline.

However, the B1 scenario, which shows a decline in global emissions, is very likely to require a decline in U.S. emissions as well. While it is possible that U.S. emissions might rise while global emissions decline, this appears very unlikely. If global emissions decline, it is very probable that U.S. emissions will decline as well, and from similar causes. There are multiple circumstances that might produce an emissions outcome consistent with a global B1 scenario, including technological change, economic, environmental, or political developments, or changes in social preferences. One such circumstance would be U.S. participation in effective multinational climate mitigation strategies.[145]

Transportation accounts for 28 percent of US carbon dioxide emissions and is the fastest growing global source of emissions.[146] If "deep cuts in global greenhouse gas emissions are required" and if the international community is to achieve "a global goal of substantially reducing global emissions by 2050,"[147] then mitigation action to reduce U.S. greenhouse gas emissions in general and in the U.S. transportation sector in particular will eventually be desirable. While the content of future U.S. emissions are uncertain, in a B1 scenario, actions that reduce U.S. emissions are likely to affect the structure of the U.S. energy sector and the U.S. economy over the next century, and these changes are likely to affect the transportation sector, beyond the changes in transportation sector operations.

The transportation sector has relatively high mitigation costs. However, a situation in which U.S. emissions decline along with the rest of the world will probably include reductions in the transportation sector, at least in part, because transportation sector reductions are necessary produce very large reductions in aggregate U.S. greenhouse gas emissions.

The transportation sector includes large-scale infrastructure for the bulk transportation and distribution of fossil fuels, including national-scale networks of pipelines and terminals for the distribution of crude oil, refined petroleum products, and natural gas. There is an extensive rail infrastructure for the shipment of coal, particularly from the huge surface mines of North Dakota, with delivery to electric power plants in the Midwest and Appalachia. Climate mitigation policies that affect fossil fuel consumption will affect these systems as well.

Whatever energy sources are substituted for fossil fuels would require their own, probably distinctive, transportation infrastructure.

Finally, there are many possible measures that reduce greenhouse gas emissions, both within and outside transportation sector, all of which have at least some impact on transportation. The measures discussed in this report have been selected because they have the greatest potential to produce national-scale impacts on transportation. Such measures are not necessarily the most cost-effective strategies, nor the most likely to be implemented.

B. **Reduction in Coal Consumption**

The United States produces and consumes more than 1 billion short tons of coal every year. In 2010, about 93 percent of the 1.05 billion tons coal consumed in the United States was used to generate electric power.[148] While coal is produced in 25 States, the Powder River Basin, largely in Wyoming, accounted for some 468 million tons of production 2010, or 43 percent of U.S. coal production, followed by Appalachia (West Virginia, Kentucky, Tennessee, Virginia, and Pennsylvania) with 335 million tons (31 percent), and the Illinois Basin (Illinois and Indiana) with 105 million tons (10 percent).[149]

U.S. coal consumption is broadly centered on the area surrounding the Appalachian Mountains: the Midwest accounts for 39 percent of 2010 coal consumption, followed by the interior South (25 percent), and the Mid- and South Atlantic States (21 percent), and the Mountain States (11 percent).[150]

In 2007, rail accounted for 72 percent of coal shipment tonnage, with an average haul distance of 428 miles, while trucks accounted 15 percent of shipment tonnage, but with an average haul distance of only 61 miles.[151] Some 418 million tons of coal were shipped out-of-state from Wyoming by rail in 2010, largely to the Midwest and South.[152] "On a typical day," 70-80 coal unit trains, averaging 130 cars in length, leave the Powder River Basin.[153] Figure 17 illustrates the national pattern of coal shipments by rail, including the flow from Wyoming to the Midwest.

In terms of its economic value, coal is a minor commodity for the U.S. freight transportation system: in 2007 it accounted for only 0.3 percent of the value of shipments. However, in physical terms, coal accounts for 10 percent of freight tonnage, and 25 percent of freight ton-miles.[154]

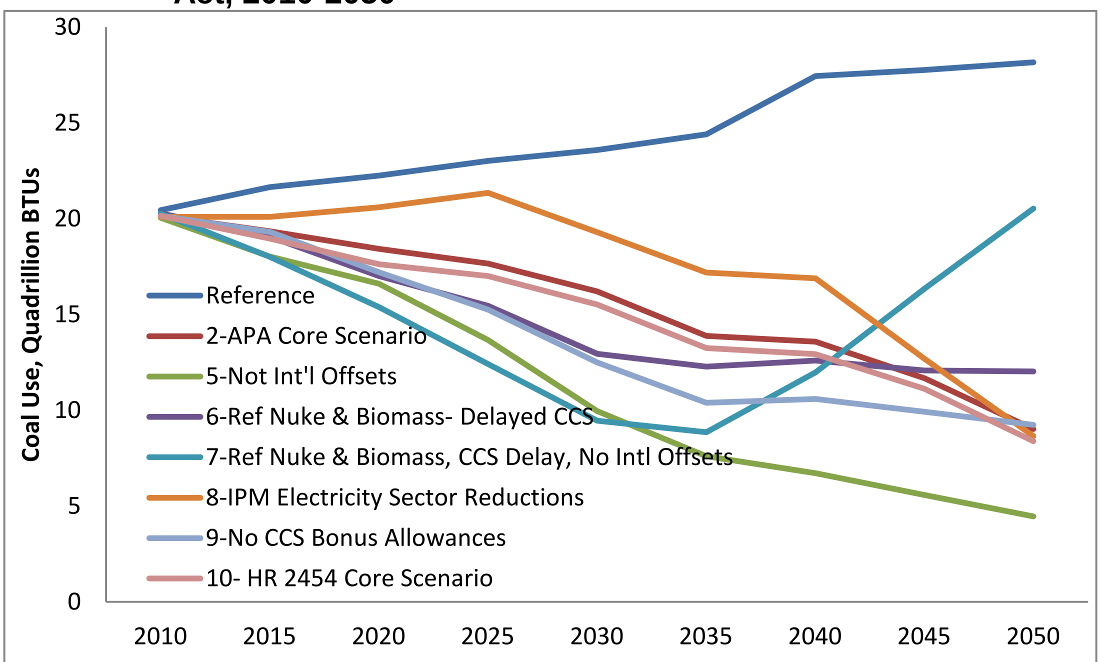
U.S. coal combustion accounted for 1.8 billion metric tons of carbon dioxide emissions in 2009, about a third of U.S. energy-related carbon dioxide emissions, and about 28 percent of net greenhouse gas emissions measured in carbon dioxide equivalents.[155]

Energy-economic modeling suggests that market-based constraints on U.S. greenhouse gas emissions will lead to large-scale reductions in coal consumption. The technologies that replace conventional coal consumption vary, as do the extent of the reduction, but the general picture that emerges is that reductions in coal use are a relatively low-cost mitigation strategy in the United States. For example, the Environmental Protection Agency's recent modeling of the American Power Act and H.R. 2454, suggested reductions in coal-fired power generation of 50 percent (compared with 2015) by 2050 in most scenarios (Figure 18).[156]

Figure 17. Coal Shipments by Rail, 2007

Source: US Department of Agriculture and US Department of Transportation, *Study of Rural Transportation Issues* (April 2010), p. 171. (Chapter 5: Coal Transportation). Original source was an FRA review of 2007 Waybill Sample.

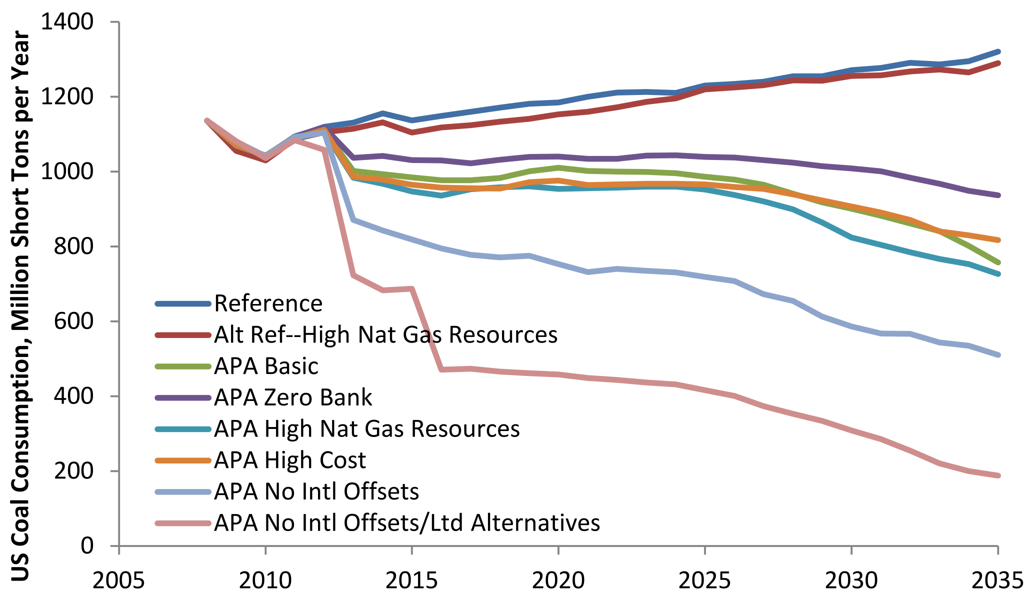
Figure 18. EPA Projections of U.S. Coal Use Under the American Power Act, 2010-2050



Source: Environmental Protection Agency, *EPA Analysis of the American Power Act in the 111th Congress*, (June 14, 2010).

Similar examples can be drawn from the Energy Information Administration's two recent service reports: a report on the impacts of the proposed-but-not-passed American Power Act, and also a report on the consequences of a Clean Energy Standard for the electric power sector. EIA's modeling framework has a shorter time horizon than that of EPA, so EIA projections usually extend only to 2035. The structure of EIA models differs from that of the EPA, and the views of EIA analysts about cost and performance of future technologies (as embedded in modeling assumptions) may vary as well. However, the big picture is similar: market-based policy interventions aimed at limiting greenhouse gas emissions will tend to cause large reductions in U.S. domestic coal use. Figure 19 illustrates EIA's view of the proposed American Power Act.[157] The extent of the reduction in coal consumption would depend on the stringency of the limitation on carbon emissions, the detailed design of the policy instruments used, and a future cost, price, availability of resources, and the relative cost and availability of advanced technologies. One of the particular features of the proposed American Power Act was the prospective availability of a limited quantity of international carbon credits (or offsets) available to reduce the effective stringency of the regime. Since the future relative price and availability of international offsets is uncertain, both EPA and EIA considered scenarios with differing amounts of credits. In both EPA and EIA modeling, the extent of reduction in coal use was greatest in scenarios in which no international offsets were available.

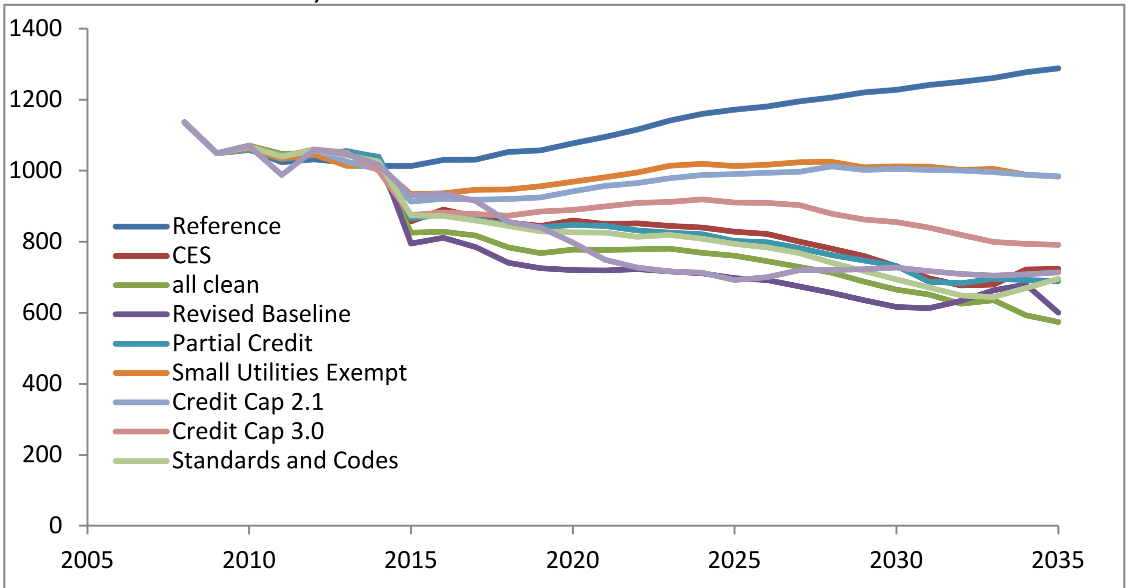
Figure 19. EIA Projection of U.S. Coal Use Under the American Power Act, 2010-2035



Source: Energy Information Administration, *Energy Market and Economic Impacts of the American Power Act of 2010* (July 2010)

Figure 20 shows projected coal consumption from a more recent EIA service report, which considered the effects of a clean energy standard aimed at reducing electric power sector greenhouse gas emissions 50 percent by 2050.[158] The results are generally consistent with the earlier EIA analysis: the cases where coal consumption reductions are smaller tend to be cases in which exemptions from the clean energy standard tend to limit the reduction in total emissions.

Figure 20. EIA Projection of U.S. Coal Use Under a Clean Energy Standard, 2008-2035



Source: Energy Information Administration, *Analysis of Impacts of a Clean Energy Standard*, (Nov. 2011).

EIA models also report on the projected regional distribution of coal production. For smaller total reductions in coal use, reductions are concentrated in Appalachia. However, for very large reductions, Western coal (meaning primarily Powder River Basin coal) declines even more than in Appalachia.

For the transportation sector, domestic reductions in greenhouse gas emissions generally consistent with the global scale reductions in carbon dioxide emissions envisioned in the IPCC B1 scenario are likely to manifest themselves as reductions in coal flows by 50 percent or more. This implies reduction in freight movement of hundreds of billions of ton-miles, equivalent to 10 percent or more of total ton-mile shipments.

It should be noted that this outcome might be induced by exogenous technological change, by the discovery of new resources, by public policy unrelated to climate change, or various economic developments, as well as a domestic mitigation policy. Thus, it is a possible outcome in both the A2 and B1 scenarios, but a more likely outcome in the context of a B1 scenario.

If coal usage were to decline rapidly, there would be a large physical impact on shipments in the rail and barge industries, and some specialized infrastructure would become obsolete, or at least underused. The industries that formerly moved the coal would incur economic costs. The national economic impact, however, would be contingent on the cost and value of whatever replaces coal. In principle, coal usage wouldn't decline rapidly unless the value of the replacement energy source(s) with or without environmental benefits was greater than the losses from coal production and transportation. Therefore, while the physical effects would be large, if this outcome were to occur, the national-scale economic effects would likely be positive.

C. **Carbon Capture & Sequestration**

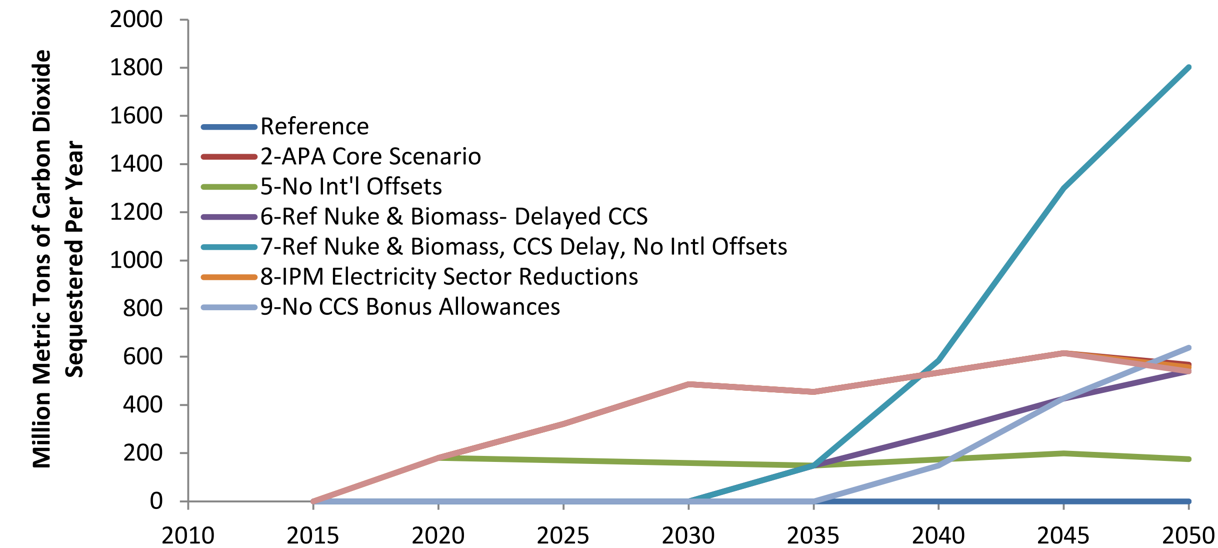
All of the modeling results presented in the previous sections provide for the use of carbon capture and sequestration (CCS) as a technological option, at varying projected costs and operating efficiency. Thus, the reductions in coal use described in the previous section are **net** of any projected application of carbon capture and sequestration technology to electric power generation. Carbon dioxide may be separated either prior to combustion by purpose-built new integrated gasification combined cycle (IGCC) power plants, or post combustion via retrofit or possibly attached to a new conventional steam turbine. IGCC plants have higher thermal efficiency and would probably produce electricity at a lower total cost, but retrofits may be attractive under specific circumstances. Once the carbon dioxide has been separated, it must be compressed to very high pressures, transported to a suitable geologic reservoir, and injected into the ground. Carbon dioxide injection fields will probably require long-term monitoring to ensure that the carbon dioxide remains safely sequestered.

While many advanced energy technologies may become commercial independently of the policy environment, carbon capture and sequestration is only likely to be developed on a large scale in the context of policies to reduce greenhouse gas emissions. Compared to a conventional IGCC plant, an IGCC plant with carbon sequestration may have 40-percent higher capital costs and 20-percent lower thermal efficiency.[159]

While carbon capture and sequestration may preserve the coal industry, it poses its own set of challenges to the transportation sector. On average, each ton of coal combusted in the United States generates two tons of carbon dioxide emissions.[160] If carbon sequestration comes into large-scale use, the volumes of carbon dioxide requiring transportation to sequestration sites are potentially immense.

Figure 21 illustrates EPA estimates of the volumes of carbon dioxide captured and sequestered under the various American Power Act carbon reduction scenarios introduced in Figure 18. In EPA's scenarios, only minor amounts of carbon dioxide are sequestered prior to 2015, and most scenarios sequester about 500-600 million tons of carbon dioxide annually by 2050. However, in Scenario 7, where the model is constrained from adding additional nuclear capacity and no international offsets are permitted, carbon sequestration reaches 1.8 billion metric tons annually, approximating current U.S. carbon dioxide emissions from coal, and a quantity considerably greater than current total national coal production or reported coal shipments.

Figure 21. **EPA Projections of CO_2 Capture Under the American Power Act, 2010-2050**



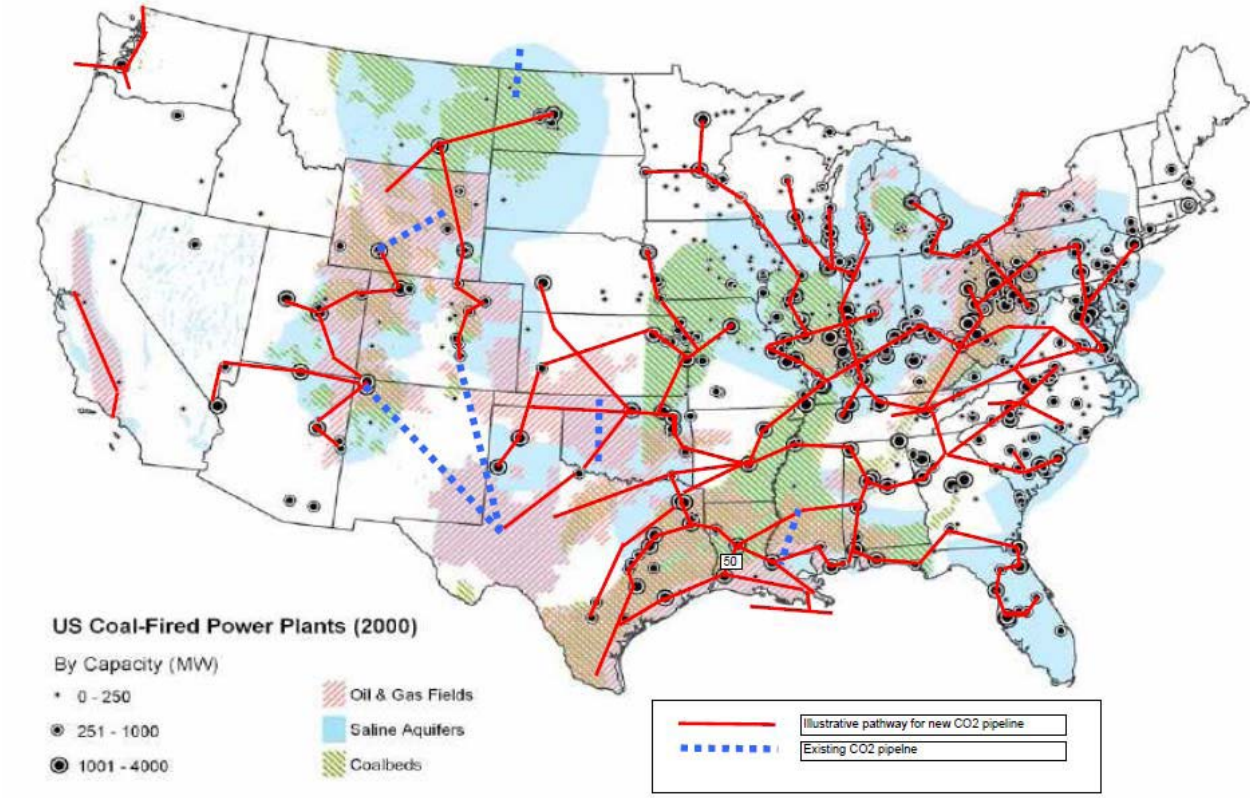
Source: Environmental Protection Agency, *EPA Analysis of the American Power Act in the*

The nature of the transportation challenge posed by carbon capture and sequestration depends to a large degree on the scale on which carbon capture and sequestration is implemented. In general, single projects are likely to use a single geologic sequestration site, linked to the power plant by a single point-to-point pipeline. Single projects in oil producing areas or close to the existing carbon dioxide pipeline system may link an oil field or existing pipeline system and supply carbon dioxide for enhanced oil recovery.[161]

Carbon capture and sequestration raises major transportation issues only if CCS projects begin to proliferate. If there are multiple large projects, each generating millions of tons of carbon dioxide annually, some combination of economics, technology, and regulatory regime may begin to favor concentrating geologic sequestration in a few large sites. This is a possible outcome, but by no means a foregone conclusion. However, if concentrated sequestration proves desirable, then it must be implemented through a network of dedicated carbon dioxide pipelines. Figure 22 illustrates one such hypothetical network, as envisioned by a natural gas pipeline trade association. This network links the locations of existing large coal-fired plants (and some industrial sources) with areas favorable for geologic sequestration, as well as oil production regions and to the existing enhanced oil recovery-oriented carbon dioxide pipeline network. This system assumes up to 1 billion metric tons of annual carbon sequestration, circa 2030.

The authors consider two CCS cases: a high case with about 1 billion tons per year stored, and at a pipeline capital cost of $32 to $65 billion to build some 36,000 miles of pipeline, notionally by 2030; and a 300 million ton per year low case, with a pipeline capital cost of $8 - $13 billion.[162]

Figure 22. CO_2 **Carbon Capture and Sequestration Pipeline Network, circa 2030**



Source: INGAA, *Developing a Pipeline Infrastructure for CO_2 Capture and Storage: Issues and Challenges* (February 2009), p. 66. See: http://www.ingaa.org/File.aspx?id=8228

A risk assessment for carbon capture and sequestration is particularly challenging. CCS is very unlikely to appear on a national scale in the absence of public policy aimed at reducing carbon dioxide emissions. While public policy is probably necessary for large-scale CCS to appear, it is not sufficient, because there are other possible methods of reducing emissions in the electric power sector. Secondly, if CCS is deployed on a large scale, and geologic sequestration is largely local, transportation implications will be minor.

Finally, there is the common problem of the metric for an "effect." Building a national network of carbon dioxide pipelines at a cost of $30 billion or more certainly qualifies as a physical effect, but such a system would only come into existence if there was a public consensus that the benefits of limiting emissions exceeded the costs, and the funds to finance the creation of a carbon dioxide pipeline network could be successfully raised by the private sector, on the basis that the system could be run at a profit. So, a carbon dioxide pipeline network would produce positive economic benefits for the transportation sector, net costs for the electric power sector, and a balance of national benefits and costs that would be presumptively positive.

D. **Large Scale Energy Use of Biomass**

Another possible large-scale alternative or supplement to the use of fossil fuels is biomass. Biomass has been the primary source of supplementary energy for most of human history, and it continues to be an important source of household energy in much of the world.[163] The United States, with its immense land area, extensive forest cover, and large areas of cultivable but uncultivated land, generates immense volumes of biomass, and can produce more.
Biomass energy is thus a possible pathway into a low-carbon future, and consequently might play a large role in a Scenario B1 world. Biomass might play several roles in such a world:

- Public policy might aim at large-scale carbon sequestration, most likely by expanding forests, but potentially including other methods as well;
- Biomass might be combusted as an alternative to fossil fuels such as coal for generating electricity and heat, possibly with carbon sequestration.
- Biomass might be converted into liquid or possibly gaseous fuels for use in the transportation sector.

Large-scale forest carbon sequestration does not have major implications for the transportation sector, since nothing requires delivery or shipment. Small-scale or local biomass energy or biomass conversion to transportation fuels can be accommodated within the existing transportation system, and hence does not have systemic implications for the transportation sector. For example, corn-based ethanol production has grown from negligible levels to more than 13 billion gallons per annum over the past decade, and biodiesel production exceeds 1 billion gallons.[164] In general, the diversion of corn to a network of newly constructed ethanol plants, and the delivery of ethanol by rail car to end user markets has not required any major expansion of transportation networks.

Further development of biomass for transportation fuels has been required by the Energy Independence and Security Act of 2007 (EISA), which requires the production of 22 billion gallons of "advanced biofuels" by 2022.[165] Development of biomass in the context of a low emissions scenario would likely be in amounts greater than that required by EISA.

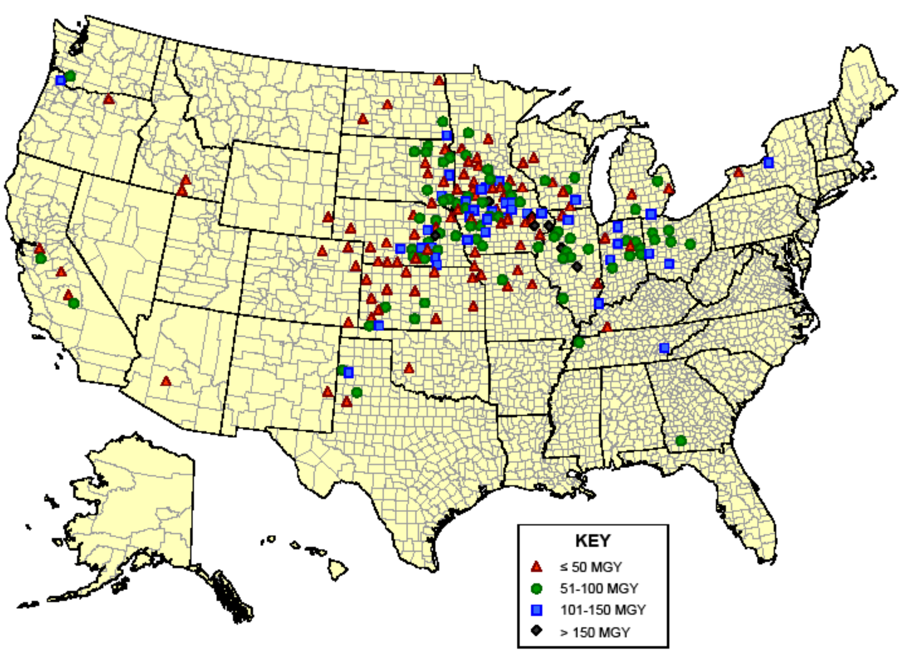
Since the EISA amounts are about three times larger than current biofuel production, production of biomass energy or liquid biofuels beyond the amounts required by EISA could potentially have significant transportation consequences. Biomass takes many forms, but almost all forms of biomass have an energy density significantly lower than that of fossil fuels. Since biomass is the product of a relatively inefficient transformation of sunlight into stored chemical energy, only modest amounts of potential energy can be harvested per unit of land area.

Biomass is typically at least 20-percent moisture by weight, and may be as much as 50-percent. About half of the dry weight is oxygen. Consequently, the energy-containing element in biomass may only be 30-40 percent of its total weight. For liquid transportation fuels, a pound of fuel will typically require three to four pounds of biomass dry feedstock.[166]

The distribution of biomass feedstocks inevitably affects the scale and distribution of biofuel conversion plants. Even in the event of large-scale use of biofuels, biorefineries are likely to be small and located close to feedstock sources, since reducing transportation costs is more important than minimizing production costs through economies of scale.[167]

This has proven to be the case for corn-based ethanol, even though corn is rich in carbohydrates and sugars, and hence has higher energy density than cellulose. There are 193 ethanol plants in the United States, mostly situated in the Corn Belt (Figure 23), with an operable capacity of 0.9 million barrels per day (14.2 billion gallons per year), and mostly of similar size.[168] Crude oil can be economically transported half-way around the world by tanker, refined in Texas, and the products shipped by pipeline to consuming markets as far away as New Jersey. By contrast, biofuel feedstocks will likely be hauled by truck over a relatively short distance to a small local biorefinery, and the product shipped by railcar or possibly barge to distant markets.

Figure 23. Location and Size of Current Corn Ethanol Plants



Source: Environmental Protection Agency, *Renewable Fuel Standard (RFS2) Regulatory Impact Analysis*, [EPA-420-R-10-206) (March 26, 2010), p. 263. See: http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

The magnitude of future biofuels production will depend on multiple factors, particularly improvements in process economics, but one limiting element is the availability of feedstocks. Oak Ridge National Laboratory, in its 2005 "billion ton study," concluded that the United States could potentially produce almost 1 billion dry short tons of biomass feedstocks annually and "still continue to meet food, feed, and export demands."[169] A 2011 update indicates that up to

1.4 billion dry short tons of biomass could be available for energy use by 2030.[170] The authors estimated both the type and spatial distribution of biomass, but did not suggest that they considered climate change impacts on cropping patterns and fertility in preparing this study, but as the time horizon for the study is 2030, climate impacts may be minor at that point.

The study estimates that about 328 million tons of biomass is currently in use, leaving net availability of 0.8 – 1.3 billion tons. The biomass requirement for EISA is in the range of 200-300 million metric tons, depending on the future conversion efficiency of biomass feedstocks to biofuels.[171] EPA's *Regulatory Impact Analysis* indicated that most of the feedstocks for meeting EISA requirements will come from agricultural and forestry residues, which the *Billion Ton Update* indicates may total some 370- 500 million tons in 2030.[172] Presumably the lowest cost feedstocks are likely to be used first, so that the last few hundred million tons of waste feedstocks will be relatively expensive.

The most likely outcome is that expansion of biomass energy beyond the provisions of EISA will largely require the use of energy crops. The *Billion Ton Update* indicates a potential resource for energy crops of 400 – 800 million tons grown on currently uncultivated lands, which comprise some mix of switchgrass and woody crops, fed to cellulosic biofuel plants.

The maximum scale for cellulosic biofuel plants appears to be relatively small. In the EPA *Regulatory Impact Analysis*, EPA pegged the scale of cellulosic ethanol plants at 100 million gallons per year, requiring the feedstocks be drawn from a radius of 100 miles or less.[173] DOE's recent work on reference cellulosic plants suggests 50 million gallons per year, with shipment radii of about 45 miles.[174] One study suggested that, taking into account transportation costs, the optimal plant size was 25 million gallons per year.[175] The two largest cellulosic plants that EPA expects to begin to production in 2012 (KiOR and INEOS) have production capacities of 11 and 8 million gallons per day, respectively.[176]

Plant scale is important because it defines the area from which feedstocks may be drawn, which in turn helps defined the scale of the impact on the transportation sector. In general, the larger the plant size, the more truck transportation will be required, since each ton of feedstock will have to be transported over a greater distance. Since biomass feedstocks are not very dense, truck loads are typically volume, rather than weight-limited, and the Table 8 illustrates:

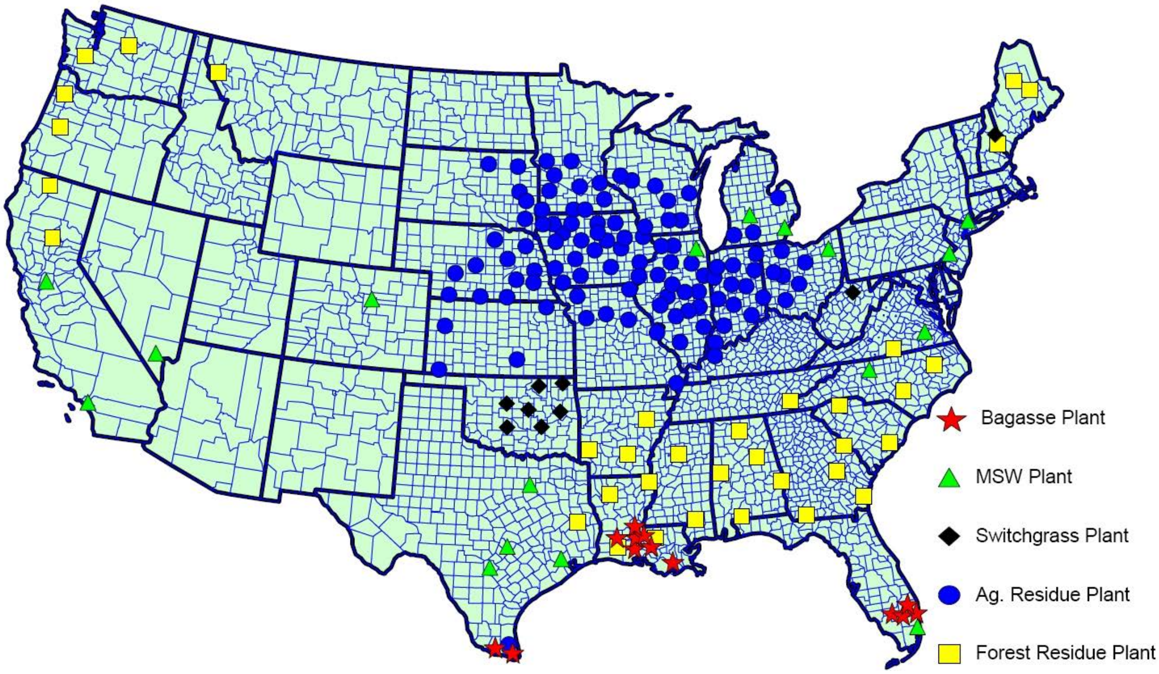
Table 8. Feedstock Transport for 100-Million GPY Cellulosic Biofuel Capacity

Number and Size of Producing Plants	Assumed Radius (Miles)	Million Ton Miles	Million Vehicle Miles Traveled	
			12 Tons per Truckload	25 Tons per Truck Load
4 x 25 million gpy	25	26	3.8	1.6
2 x 50 million gpy	50	52	7.6	3.8
1 x 100 million gpy	100	104	15.3	7.6

Notes: "Gpy" = gallons per year. Total feedstock required is 1.2 million short tons, delivered in 140/293 truck round trips per day. Assumes average trip length 71 percent of radius, moisture content 12 percent at time of transport, Plant yield of 78 gallons ethanol per dry ton feedstock.

The 100 million gallons of cellulosic ethanol (weighing 330,000 tons) would be delivered by some combination of truck, rail, and barge. EPA's calculation of hypothetical locations for 100 million gallon-per-year cellulosic ethanol plants induced by EISA is shown in Figure 24.

Figure 24. Projection of Cellulosic Ethanol Plant Locations & Feedstock, 2022



Source: Environmental Protection Agency, *Renewable Fuel Standard (RFS2) Regulatory Impact Analysis*, [EPA-420-R-10-206] (26 March 2010), p. 281. http://www.epa.gov/otaq/renewablefuels/420r10006.pdf

In a B1 scenario, some fraction of the 400-800 million tons of potential energy crops, as well as the more costly of the agricultural and forestry residues would likely be tapped. EIA, in its modeling of limitations on greenhouse gas emissions, considered the potential for biomass energy use in the electric power sector. Their modeling suggested that about 2 quadrillion Btu of additional biomass energy would be used for electric power generation, mostly in the form of biomass co-firing in electric power plants. This equates to about 150 million tons of woody biomass. EIA did not, however, specify the exact source of the biomass. EIA projected relatively small amounts of biofuel production, implying that biomass co-firing is often a more economically attractive use of low-cost biomass feedstocks than ethanol production. In the EIA projection, biomass co-firing peaks in the late 2020s, and then declines, probably because closing of coal-fired plants eliminates local opportunities. It is tempting to conclude that EIA's 150 million tons of feedstocks represent some sort of economic upper limit on biomass use in the electric power sector.

Hence, in more stringent policy regimes than those modeled by EIA, biofuels production may be relatively more attractive, particularly, since, as noted above, hauling biomass long distances can be very costly. In addition, the high cost of biomass transportation makes real-world comparative economics sensitive to location-specific considerations that may not be adequately represented in national-scale models.

However, in terms of national-scale transportation sector impacts, that biomass is mobilized, generating demand for freight transportation, may be more important than the precise use to which it is put. If 150 million tons of biomass needs to be moved, it doesn't matter whether it is moved to a biofuels plant or an existing coal-fired plant. For biomass coal-firing, typically two tons of biomass is required to substitute for a ton of coal. The ton of coal, however, will have traveled long distances (probably) by rail, while the two tons of biomass will have traveled (probably) a short distance by truck.

Table 9 details some of the potential transportation consequence of a large scale move to biofuels development in the United States, with a calculated deployment of 10 – 50 billion gallons of biofuels annually over and above the 36 billion gallons required by EISA. By comparison, current U.S. gasoline consumption is about 140 billion gallons annually, and current U.S. ethanol production is 13 billion gallons. The EISA 2022 target is 36 billion gallons.

Table 9. Freight Transportation Implications of Cellulosic Biofuel Production

National Production of Cellulosic Ethanol and Plant Size	Number of Plants Required	Feedstock Used (million tons)	Share of 2007 Truck Ton-Miles (Percent)	Share of 2007 Truck VMT (Percent)	Share of 2008 Rail Ton-Miles (Percent)
10 billion gallons					
25 million gpy	400	100-139	0.2 – 0.3	0.1 – 0.3	1.5
100 million gpy	100	100-139	0.6 – 0.8	0.3 – 1.0	1.5
25 billion gallons					
25 million gpy	1,000	250-347	0.5 - 0.7	0.3 – 0.7	3.8
100 million gpy	250	250-347	1.5 - 2.1	0.8 – 2.4	3.8
50 billion gals					
25 million gpy	2,000	500-694	1.0 - 1.3	0.5 – 1.3	7.6
100 million gpy	500	500-694	3.1 - 4.1	1.7 – 4.9	7.6

Notes: Feedstock assumes 72 – 100 gallons per ton yield. Truck-ton miles assume feedstock range plus 25 – 100 mile radius for plant use, plus 30-mile consumer distribution of ethanol by truck. Truck VMT assumes feedstock range plus 12-25 ton payload per truck for feedstock, plus 25-ton payload per truck for each 30-mile ethanol distribution trip. Rail ton-miles assume 800-mile average rail shipment for each ton of ethanol. National truck VMT definition used was "combination truck."

Sources: U.S. truck and rail ton-miles, from: Bureau of Transportation Statistics, *National Transportation Statistics*, Table 1-49. See: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_35.html US truck VMT from Federal Highway Administration, *Federal Highway Statistics 2009*, Table VM-1. See: http://www.fhwa.dot.gov/policyinformation/statistics/2009/vm1.cfm Rail delivery distance, distribution distance, ethanol truck load per vehicle drawn from assumptions in GREET 1_2011 spreadsheet, as distributed by Argonne National Laboratory. http://greet.es.anl.gov/ For basis of other assumptions, see text of report and Table 8.

The values in Table 9 span the scope of the freight impacts of a large-scale deployment of cellulosic ethanol reaching beyond the targets of EISA. The high end of the range (50 billion gallons) would use most of DOE's potential 2030 energy crop biomass feedstock for fuels, which includes a considerable increase in crop yields. The low end of the range might be encompassed within existing and potential agricultural and forestry residuals.

While these calculations are built around a notional cellulosic ethanol industry, they are largely independent of the particular technology chosen. There are multiple engineering pathways from biomass reduced net carbon emissions, and multiple pathways from cellulosic biofuels to transportation fuels. Some pathways generate ethanol, while others generate "drop in" hydrocarbon replacement fuels, from gasoline to jet fuel. The ethanol-blending-in-gasoline market will be largely saturated by corn-based ethanol, so an advanced biofuel-as-ethanol industry will have to develop an extensive E85 infrastructure even under EISA. On the other hand, the biomass-to-hydrocarbon technologies may involve additional complexity. It is not apparent, at this juncture, which if any of the current emerging technologies will prove commercially successful at scale. All of the fuel pathways share the characteristic that they will require the transportation of very large volumes of feedstocks to produce nationally significant volumes of biofuels.

At the national scale, the impacts on the freight system of even a large-scale biomass deployment appear manageable, particularly since it is likely that in any scenario where there is large-scale biomass freight transportation is also a scenario where coal transportation is likely to decline as well. In addition, there may be particular routes which are subject to congestion. Further, while individual biorefineries might crop up in urban areas, most such plants will have to be in rural areas, so the impact of the additional truck traffic on urban congestion is likely to be modest. However, the impacts on particular rural communities may be significant.

A beyond-EISA cellulosic biofuels strategy looks more probable in a B1 scenario than an A2 scenario. If this industry develops, the effects on the freight system appear moderate. As in other cases, consequences here apply to physical consequences. In principle, conditions that would give rise to a national-scale cellulosic biofuels industry should produce economic net benefits.

E. **Hydrogen Infrastructure**

Hydrogen is another alternative to fossil transportation fuels. As in other cases, alternatives to fossil transportation fuels are most likely to appear in the context of a low emissions scenario, whether induced by climate mitigation, technological evolution, or both. While hydrogen can be used in internal combustion engines, it is most likely to appear in concert with fuel cells as an energy storage medium for electric vehicles: essentially an alternative to batteries. While fuel cells typically have higher thermal efficiency than internal combustion engines, national-scale hydrogen use will require very large volumes of hydrogen, manufactured by breaking up molecules of hydrogen-containing compounds (usually hydrocarbons or water).

If hydrogen is implemented as a climate change mitigation strategy, it must then be implemented in ways that are less carbon-intensive than gasoline, which restricts the possible pathways by which hydrogen can be manufactured. In order to influence transportation systems, hydrogen must be implemented on a sufficiently large scale to produce national-scale transportation effects in the form of national-scale dedicated transportation infrastructure. The leading candidate hydrogen sources are:

- Fossil fuel gasification with carbon sequestration. Coal or natural gas is heated, converted to a hydrogen/carbon monoxide synthesis gas. Hydrogen is separated for use as a fuel, and the carbon dioxide is sequestered in the ground. Excess heat from the process is used to generate electricity. This process would typically take place in a relatively small number of large-scale plants, probably located at or near existing coal-fired power plants.

- Biomass conversion with or without carbon sequestration. Biomass can be gasified to synthesis gas, converted to a bioliquid through pyrolysis, or (potentially) subjected to microbial action.[177] The resulting hydrogen is separated for use as a transportation fuel, and waste carbon dioxide may be either vented to the atmosphere (for zero net emissions) or sequestered (for negative emissions).

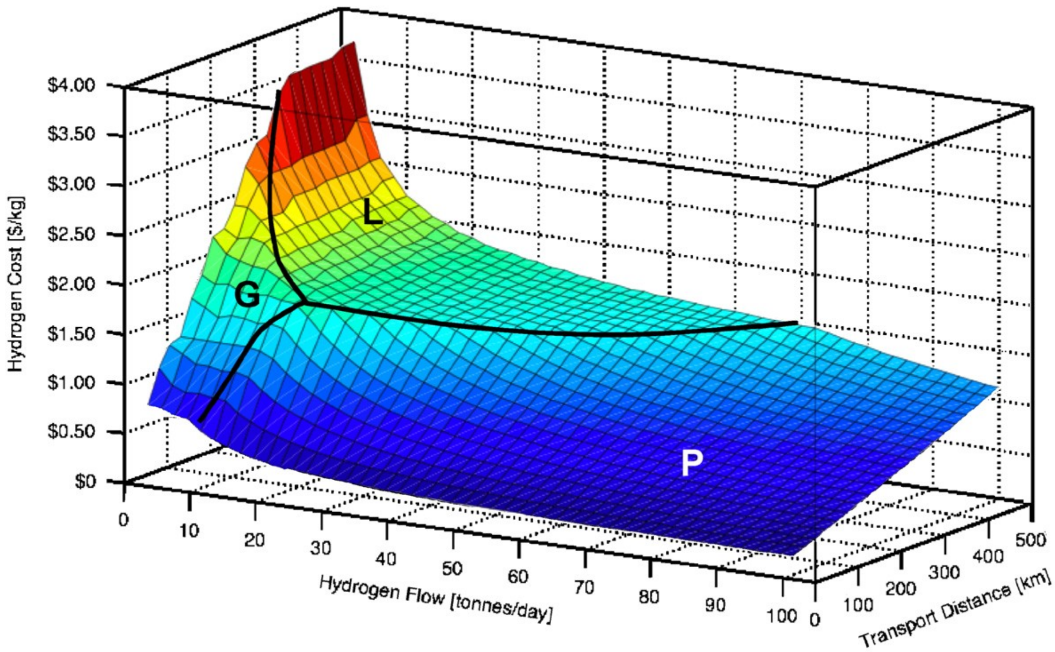
- Thermochemical decomposition of water in nuclear power plants. Water molecules decompose into hydrogen and oxygen when heated to temperatures above 700° C.[178] requiring advanced reactor designs to provide sufficient heat. This pathway would be contingent on extensive construction of new technology nuclear power plants.[179] The approach implies a relatively small number of large central systems, located where nuclear plants might be sited.

- Electrolysis of water using electricity. Electrolysis can be done on small or large scales, but it is most attractive as a small scale, distributed hydrogen production system that does not require a dedicated hydrogen production and delivery infrastructure. Electrolysis is a relatively costly and energy intensive method for manufacturing hydrogen.[180] For climate mitigation, zero or low emissions electricity would be required.

The most common current approach to making hydrogen is steam reforming of natural gas, which can be done either in large central plants or (at extra cost) in smaller distributed facilities. However, a hydrogen pathway based on steam reforming of natural gas without sequestration offers only modest greenhouse gas advantages over petroleum, and hence is an unlikely outcome in a low emissions scenario.[181]

Hydrogen infrastructure poses special challenges. A conventional compressed hydrogen truck can carry only 300 kg of hydrogen, while a liquid hydrogen truck can carry only 4,000 kg of hydrogen.[182] By contrast, a typical large tanker truck can carry 9,000 gallons of gasoline or ethanol (9,000 gallons of gasoline weighs 24,450 kg). So, it takes 2.25 liquid hydrogen trucks or 30 compressed hydrogen trucks to haul the same energy equivalent volume as one truckload of gasoline, making truck transportation or local distribution of hydrogen relatively expensive. The high cost of truck transportation in turn tends to make optimal hydrogen plant sizes larger, especially for biomass, and pushes transmission and distribution towards hydrogen pipelines, and encourages setting up hydrogen plants close to demand centers to minimize truck-based distribution costs.[183] One study illustrated the relative economics of hydrogen pipelines, liquid hydrogen trucks, and gaseous hydrogen trucks as shown in Figure 25.

Figure 25. **Hydrogen Transportation Costs By Flow Rate, Distance, and Mode**
(Dollars per Kilogram Hydrogen)



Note: P=Pipeline, G=gaseous hydrogen truck, L=Liquid Hydrogen Truck. $1 per kilogram hydrogen approximately equals $1 per gallon of gasoline equivalent.
Source: Christopher Yang and Joan Ogden, "Determining the Lowest-Cost Hydrogen Delivery Mode, *International Journal of Hydrogen Energy*, Volume 32 (2007), p. 277. See: pubs.its.ucdavis.edu/download_pdf.php?id=1162

An analysis of this sort depends on a host of simplifying assumptions, and would have to be modified extensively for use in any real-world situation, particularly considering rights-of-way for pipelines, which can be expensive or even unobtainable in some cases. Nonetheless, the minimum volume at which pipelines dominate alternative transportation methods is only 70 tons per day, which is the equivalent of about 35 million gallons per year of ethanol, or 1,670 barrels per day of gasoline. The implication is that, in general, even smaller hydrogen plants will be linked by pipeline rather than trucks or rail, and that an extensive new, purpose-built hydrogen pipeline infrastructure is likely to be an essential part of any future national-scale use of hydrogen as a fuel.

If biomass feedstocks are used to make hydrogen, about thirteen tons of biomass would be required to make one ton of hydrogen.[184] A (metric) ton of hydrogen is the energy equivalent of 1,000 gallons of gasoline, though the greater thermal efficiency of fuel cell vehicles would reduce the hydrogen energy input required for a light duty vehicle to travel one mile. A recent Department of Energy study indicated that the notional plant capacity for a biomass plant would be about 155 metric tons/day, (51 million gallons of gasoline equivalent per year) while a coal/CCS plant would have a capacity of 307 metric tons per day (101 million gallons of gasoline equivalent per year).[185] For biomass plants, this study estimates an average farm-to-plant distance of 40 miles. Table 10 illustrates some of the freight transportation implications of various levels of hydrogen production in the United States.

Table 10. Freight Transportation Implications of Hydrogen Production

National Hydrogen Production & Feedstock	Number of Plants Required	Feedstock Used (million tons)	Share of 2007 Truck Ton-Miles (Percent)	Share of 2007 Truck VMT (Percent)	Share of 2008 Rail Ton-Miles (Percent)
10 billion Kg H					
Coal CCS	99	78	0.0	1.2	3.0
Biomass	196	128	0.4	1.5-1.8	--
25 billion Kg H					
Coal CCS	248	195	0.1	3.0	7.5
Biomass	490	320	1.0	3.7-4.4	--
50 billion Kg H					
Coal CCS	497	390	0.1	6.0	14.9
Biomass	981	640	2.0	7.3-8.8	--

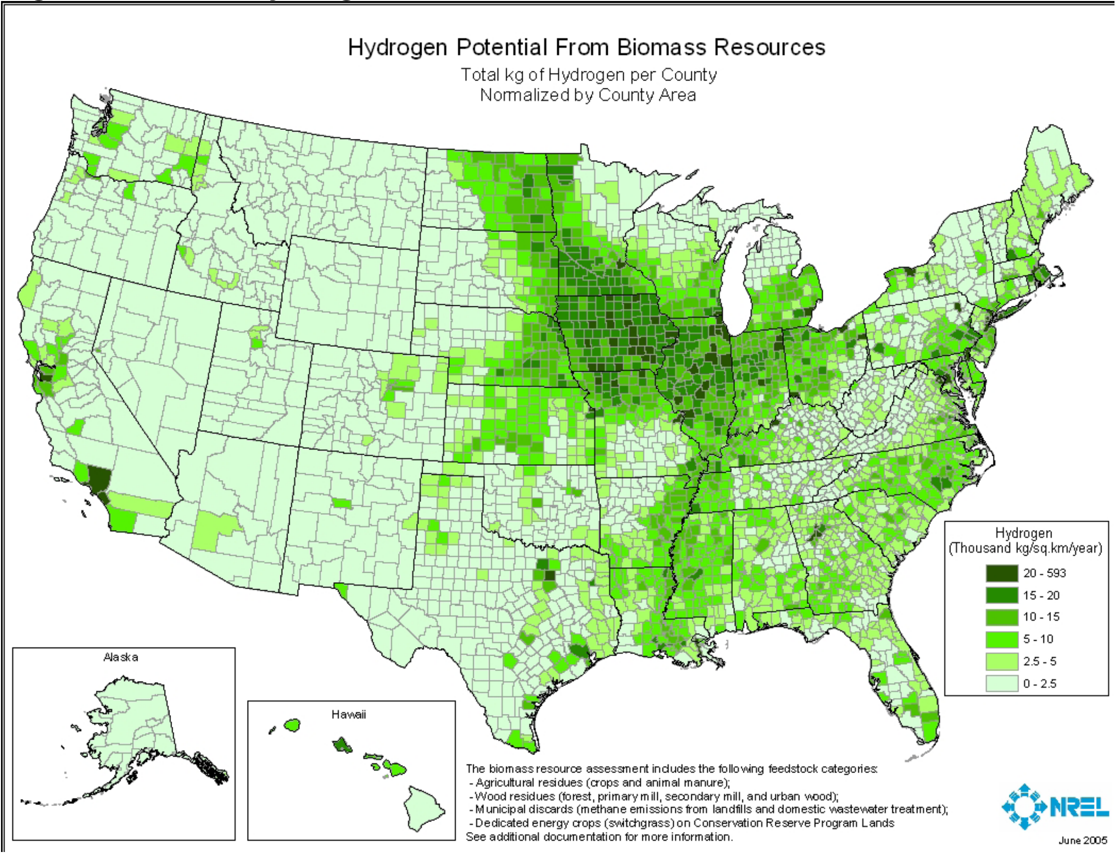
Notes: Feedstock assumes 7.8 tons coal and 12.8 tons biomass per ton hydrogen yield. Rail ton-miles assume coal transport distance 600 miles. Truck ton-miles assume biomass transport 40-miles per ton feedstock. Truck VMT assumes feedstock range plus 12-25 ton payload per truck for feedstock, plus 25-ton payload per truck for each 30-mile ethanol distribution trip. Hydrogen distribution assumes compressed hydrogen truck distribution at 300 kg per truck load, 30-mile distribution radius. National truck VMT definition used was "combination truck."

Sources: U.S. truck and rail ton-miles, from: Bureau of Transportation Statistics, *National Transportation Statistics*, Table 1-49. See: http://www.bts.gov/publications/national_transportation_statistics/html/table_01_50.html US truck VMT from Federal Highway Administration, *Federal Highway Statistics 2009*, Table VM-1. http://www.fhwa.dot.gov/policyinformation/statistics/2009/vm1.cfm Rail delivery distance (600 miles) drawn from assumptions in GREET 1_2011 spreadsheet, as distributed by Argonne National Laboratory. See; http://greet.es.anl.gov/ For basis of other assumptions, see text of report and Table 9.

Biomass hydrogen pathways require much more truck transport than ethanol pathways. Where ethanol truck transportation would be entirely rural, most hydrogen truck transport is urban, and thus would be subject to congestion externalities. It would be possible to reduce urban truck travel by using liquid hydrogen trucks, but only with a material economic penalty. It would also be possible to lay a network of distribution pipelines to connect urban refueling stations with transmission pipelines, but only at considerable expense, and with significant right-of-way issues over and above construction costs. It would be possible to avoid the urban distribution problem altogether with distributed natural gas reforming, but only by permitting carbon dioxide emissions. It would be possible to use distributed electrolysis, but at considerable economic cost, particularly if zero emissions electricity is used.

Beyond the distribution dilemma, which has both economic and operational dimensions, a coal or biomass central-station hydrogen-based system would probably require some form of long-distance hydrogen pipeline transmissions system, since moving hydrogen by pipeline would be more advantageous than moving hundreds of millions of tons of coal or biomass by truck or rail. Generally, such a system would move hydrogen out the central United States and across Appalachia and the Rockies to the heavily populated coasts. Most coal and biomass resources are located in the central part of the United States, while light duty vehicle transportation fuel use is distributed with the population (Figure 26).

Figure 26. U.S. Hydrogen Production Potential from Biomass Resources

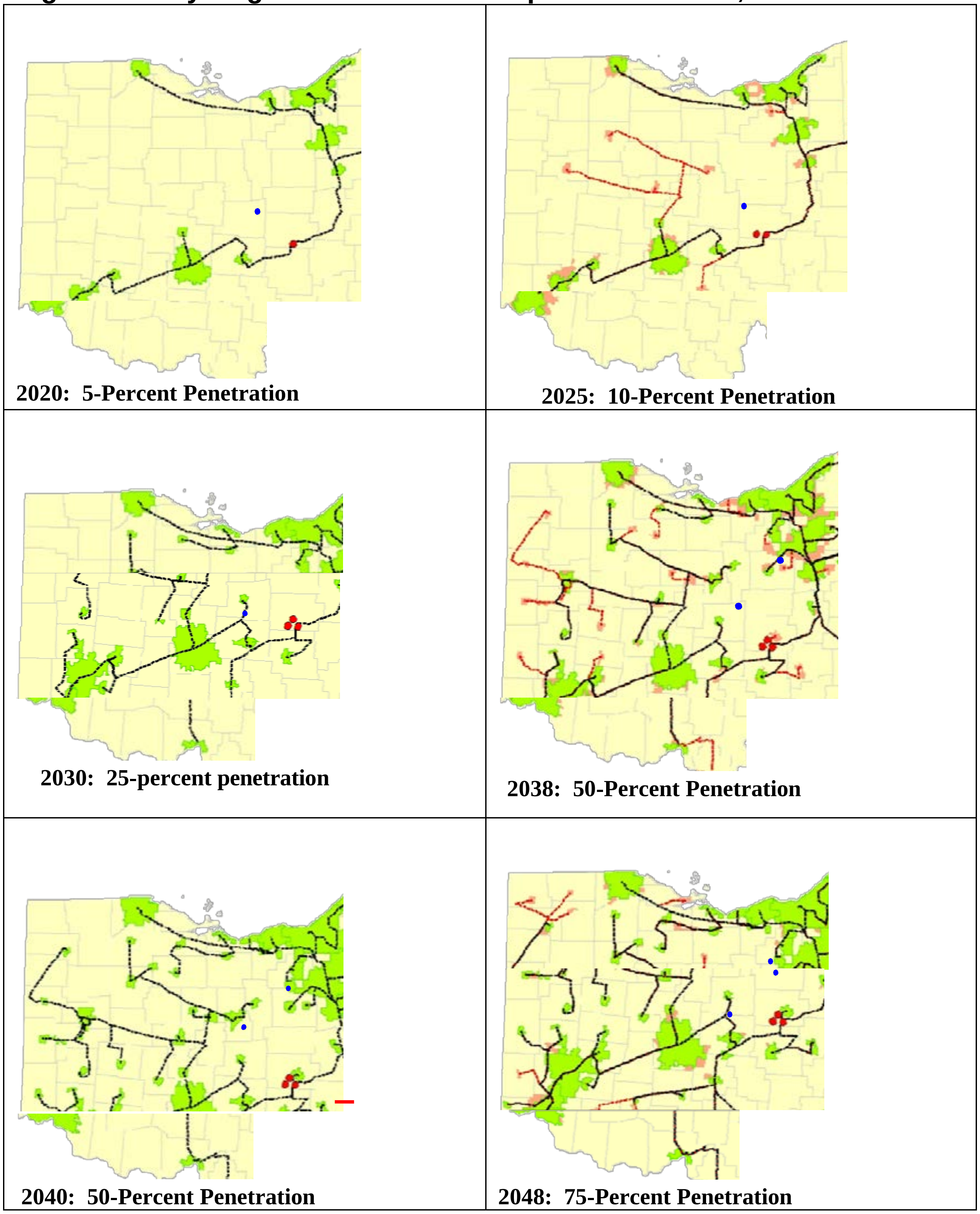


Source: Amelia Milbrandt and Margaret Mann, *Potential for Hydrogen Production from Key Renewable Resources in the United States* (National Renewable Energy Laboratory, NREL/TP-640-41134, February 2007), p. 11. See: http://www.nrel.gov/docs/fy07osti/41134.pdf

A coal-based system would have much larger plant sizes, linked to consuming centers by relatively large-diameter hydrogen transmission pipelines. Yang and Ogden (2006) consider the development of a coal/CCS based hydrogen fuel system for the State of Ohio.[186] Ohio has many large coal-fired plants and a number of large urban centers. In this study, which is nominally described as taking place between 2020 and 2050, sufficient coal-based hydrogen is deployed to raise hydrogen's share of light duty vehicle fuel consumption from negligible levels in 2020 to 75 percent of total fuel use by 2050 (Figure 27). In this scenario, Ohio is served by four coal plants with a total hydrogen capacity of 4,500 tons per day, and two carbon sequestration sites absorbing some 77,000 tons per day of carbon dioxide. Note that the average plant size in this study is more than three times larger than in the DOE study (300 tons per day) referenced above.

By 2050, 9,200 kilometers of hydrogen transmission pipeline and 5,700 km of hydrogen distribution pipeline are built, along with some 1,500 refueling stations. With only a few hydrogen plants and nearby sequestration, only 197 km of carbon dioxide pipeline is required.

Figure 27. Hydrogen Infrastructure Expansion in Ohio, 2020-2050



Notes; Blue Dots=Sequestration Sites; Red Dots=Coal-fired Hydrogen Plants; Green=areas served by hydrogen fuel; black=hydrogen pipelines; red=new hydrogen transmission lines added from previous cell.
Source: Nils Johnson, Chris Yang, and Joan Ogden. *Build-Out Scenarios for Implementing Regional Hydrogen Infrastructure*, (Proceeding of the National Hydrogen Association (NHA) Annual Conference, Long Beach, California, March 2006). See: http://hydrogen.its.ucdavis.edu/research/track2/tr2pr9

In the case of hydrogen, at least, the infrastructure requirements look significant over and above the usual considerations of how to build out a network of refueling stations. The discussion above suggests the scale and complexity of developing a nationally-significant hydrogen energy system. As a climate mitigation measure, large-scale deployment of hydrogen appears less probable than some other alternatives. As in other cases, the economic benefits would be presumed to exceed the costs, but the physical impact of a large-scale hydrogen pipeline distribution system would be large.

Smaller scale adoption in specialized markets would not require a national-level infrastructure, and hence would not have national-scale consequences. As in other cases, “consequence” in the risk assessment refers to physical consequences, generally meaning an extensive hydrogen pipeline infrastructure. The circumstances that would bring a hydrogen infrastructure into existence should ensure that the infrastructure has positive net economic benefits.

F. **Changes in Vehicle Fleets**

Reductions in petroleum consumption or transportation greenhouse gas emissions may also be induced by policy, technological innovation, or market forces. Recent studies on this topic have tended to suggest that the largest reduction potential in the U.S. transportation sector lies in improving the fuel efficiency of light duty vehicles and moving to low carbon or zero carbon fuel sources.[187] Some potential low carbon fuel sources are discussed in subsequent sections.

The Obama Administration has aggressively pursued near-term reductions in petroleum consumption and greenhouse gas emissions through joint EPA/DOT fuel economy and tailpipe greenhouse gas emission regulations for both light duty vehicles (through 2016) and heavy duty vehicles (through 2018).[188] In addition, DOT and EPA have issued a joint proposal (and intend to issue a final rule in the summer of 2012) to set fuel economy and GHG emissions standards for new model year 2017 through 2025 light duty vehicles. DOT’s proposed standards are projected to require, on an average industry fleet-wide basis for cars and trucks combined, 49.6 mpg in model year 2025. EPA’s proposed GHG standards, which are harmonized with NHTSA’s CAFE standards, are projected to require 163 grams/mile of carbon dioxide (CO_2) in model year 2025, equivalent to 54.5 mpg if the vehicles were to meet this level all through fuel economy improvements[189] These rules are projected to significantly reduce petroleum consumption and emissions from the transportation sector.

It is reasonable to expect that the design and performance of both light duty and heavy duty vehicles will continue to evolve in the future in ways that improve the environmental performance, safety, and utility of the U.S. car and truck fleets.

The impacts of such changes on the transportation system itself, however, are likely to be rather modest. Improved vehicle fuel efficiency may result in some increase in vehicle miles traveled. To the extent that electric or low carbon fuel vehicles make up an increasing portion of the light duty vehicle fleet, some specialized fueling infrastructure may be required, and the usage patterns for electric vehicles may be different than those of petroleum-fueled vehicles. Vehicle improvements will likely tend to reduce the environmental footprint of the transportation system without radically altering the system itself.

Vehicle improvement may also appear in other modes. It is likely that aircraft, locomotives, and ships will evolve over time under the same kinds of circumstances that might affect motor vehicles. Incremental improvements in aircraft or marine vessel performance are not likely to cause fundamental changes in these modes, though significant changes due to changing economic circumstances, technological innovations, or public policy are always possible.

G. **Transportation Demand Measures**

Beyond vehicles and fuels, there are a range of measures that affect the volume and mode of transportation services used by the public. While there are many such measures, the most commonly discussed can be broadly grouped into three categories:

- Provision of alternative transportation modes (for example transit or bike routes);
- Changes in urban form or land use practices;
- Measures that affect the price or cost of travel.

The NRC (2009) undertook a recent study of the interaction between the built environment and personal vehicle travel.[190] The Committee found that an extensive use of compact development (75 percent on all new development) might produce a 7-8 percent reduction in VMT by 2030, and an 8-11 percent reduction by 2050.[191] A less extensive implementation (25 percent of all new development, with smaller per capita reductions) would yield VMT reductions of less than 2 percent by 2050.

A recent meta-analysis of transportation planning studies considered various policy measures to directly reduce transportation demand, defined largely in terms of light duty vehicle miles traveled (VMT).[192] The study found that individual measures had relatively modest effects, but were more effective when combined. For example, land use policy (19 studies) reduced VMT by a median 0.7 percent in ten years and 1.7 percent in 40 years, while improvements in transit (9 studies) reduced VMT by a median 0.3 percent in ten years and 1.0 percent in 40 years. However, combining land use and transit (34 studies) reduced VMT by a median 4 percent in ten years and 16 percent in 40 years. Combining land use, transit, and road pricing polices (15 studies) reduced VMT by a median 14 percent in ten years, and 24 percent in 40 years. The author also found that the largest relative impacts were found in the cities with the lowest initial density.

It should be noted that planning studies are not data, nor are communities in the United States and abroad that conducted the underlying studies necessarily a representative sample of U.S. communities. The specific results should also be considered in the context of the large increases in population and national income (and hence VMT) that can be may expected over the next century (Figure 1, Figure 2, and Figure 3). However, the basic finding that transportation policies interact, and that transportation demand measures are most effective when they create effective travel choices, appears very plausible.

Many studies consider pricing policies. Pricing policies can take multiple forms, including congestion pricing, mileage fees, gasoline taxes, and cordon fees. Recent research suggests that the price elasticity of demand for travel, which underpins the effectiveness of such policies as demand measures, is sensitive to income.[193] Small and Van Dender estimate the price elasticity of VMT with respect to the cost of driving for the period 1997-2001 was -0.027 in the short run, and -0.107 in the long-run. This implies that 11 percent increase in the cost of driving would induce only a 1 percent decline in VMT. However, this paper also indicates that higher incomes reduce elasticity. As people become wealthier relative to the cost of driving, they become less prone to change their behavior when gasoline prices rise. This finding is important in a world in which income continues to rise, public policy causes vehicle fuel efficiency to improve rapidly, and petroleum prices remain stable. In this situation, pricing policies would be decreasingly effective in influencing travel behavior, meaning that progressively larger price changes would be required to produce a given result over time.

In assessing impacts, transportation demand measures present an analytical problem similar to assessing consequences of other climate mitigation policies. In general, such measures should be presumed to be cost-effective in the policy environment in which they take place. Thus, their economic impacts, in general, ought to be positive. In a physical sense, however, they might involve material changes to transportation systems and infrastructure.

Given the confluence of public policy considerations, national-scale transportation demand measures may well occur in a high emissions A2 scenario, and appear very probable in the context of a global low emissions B1 scenario. As noted, the economic impacts ought to be positive. The physical impacts at the national scale seem likely to be moderate, and are most likely to take the form of changes in the form of public transportation infrastructure investment.

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[144] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions & Sinks, 2000-2009*, (USEPA #430-R11-005), April 2011, p. ES-2. See: http://www.epa.gov/climatechange/emissions/usinventoryreport.html

[145] This is, in essence, a judgment about a situation that would produce declining global-scale emissions. If any single large emitter (like the United States or China) does not participate, the emissions reductions of all other participants must become proportionately larger to achieve a global outcome.

[146] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions & Sinks, 2000-2009*, (USEPA #430-R11-005), April 2011, p. ES-2. See: http://www.epa.gov/climatechange/emissions/usinventoryreport.html

[147] United Nations Framework Convention on Climate Change, “The Cancun Agreements: Outcome of the work of the Ad-Hoc Working Group on Long-term Cooperative Action under the Convention,” (Decision 1/CP.16).

[148]USDOE/EIA, *Monthly Energy Review*, November 2011, p. 84. http://www.eia.gov/totalenergy/data/monthly/pdf/sec6_4.pdf

[149]USDOE/EIA, *Annual Coal Report 2010*, November 2011, Table 6. http://www.eia.gov/coal/annual/pdf/table6.pdf

[150]USDOE/EIA, *Annual Coal Report 2010*, November 2011, Table 26.http://www.eia.gov/coal/annual/pdf/table26.pdf

[151] U.S. Department of Commerce, Census Bureau, *2007 Economic Census: Commodity Flow Survey*, (April 2010), p. 23 http://www.bts.gov/publications/commodity_flow_survey/final_tables_december_2009/pdf/entire.pdf

[152]USDOE/EIA, *Annual Coal Distribution Report 2010* (November 2011), p. 117. http://www.eia.gov/coal/distribution/annual/pdf/acdr_fullreport2010.pdf

[153]Wyoming Mining Association, *Concise Guide to Wyoming Coal* (2010), p. 2. http://www.wma-minelife.com/coal/CONG2010/ConciseGuide2010-01Sep10.pdf

[154] U.S. Department of Commerce, Census Bureau, *2007 Economic Census: Commodity Flow Survey*, (April 2010), Table 5a, p. 10. http://www.bts.gov/publications/commodity_flow_survey/final_tables_december_2009/pdf/entire.pdf

[155] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009* (April 2011) USEPA #430-R-11-005, pp. 6 and 3-3. Methane emissions from coal mining would add an additional 0.1 Gg. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

[156]U.S. Environmental Protection Agency, *EPA Analysis of the American Power Act in the 111th Congress*, (June 14, 2010). Data drawn from the appendix spreadsheet: "EPA APA Analysis – Data Annex – V2.1.xls" http://www.epa.gov/climatechange/economics/economicanalyses.html

[157]USDOE/EIA, *Energy Market and Economic Impacts of the American Power Act of 2010* (July 2010). http://www.eia.gov/oiaf/servicerpt/kgl/index.html

[158]USDOE/EIA, *Analysis of Impacts of a Clean Energy Standard*, (November 2011). http://www.eia.gov/analysis/requests/ces_bingaman/

[159]Interagency Task Force, *Report of the Interagency Task Force on Carbon Storage and Sequestration* (August 2010), p. 29. See: http://www.fe.doe.gov/programs/sequestration/ccstf/CCSTaskForceReport2010.pdf

[160]In 2009, U.S. coal consumption in the electric power sector was 936.5 million short tons; yielding aggregate carbon dioxide emissions of 1.74 billion metric tons. See: http://www.eia.gov/environment/emissions/ghg_report/pdf/tbl12.pdf and http://www.eia.gov/cneaf/coal/page/special/overview.html.

[161] Note that the dual use of carbon dioxide for enhanced oil recovery and putative sequestration credits raises certain technical and regulatory issues, but would improve the economics of carbon capture and sequestration if these issues could be resolved.

[162] INGAA, *Developing a Pipeline Infrastructure for CO_2 Capture and Storage: Issues and Challenges* (February 2009), p. 63. See: http://www.ingaa.org/File.aspx?id=8228

[163] Biomass dominated U.S. energy use until the late 19th century, when it was overtaken by coal. See: DOE/EIA, *Annual Energy Review 2011*, October 2011, Table E-1. http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb1601

[164] USDOE/EIA, *Monthly Energy Review*, December 2011, p. 143. http://www.eia.gov/totalenergy/data/monthly/pdf/sec10_7.pdf

[165] Energy Independence & Security Act of 2007, Section 202(a)(2)(B)(i)(II). Advanced biofuels are defined by the Act in terms of their life cycle greenhouse gas emissions. Corn-based ethanol is not now defined as an "advanced biofuel." "Advanced biofuels" and "cellulosic biofuels" will probably primarily be composed of ethanol or other liquid fuels made from cellulosic feedstocks, augmented with biodiesel. The text of the legislation is here: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf.

[166] A typical current biomass-to-cellulosic ethanol ratio of 72 gallons ethanol per dry ton of feedstock is equivalent to 4.22 kg of fuel per kg of dry feedstock, or 2.56 LHV Btu of feedstock for 1 LHV Btu of ethanol fuel. An advanced process, with a ratio of 100 lbs. per gallon, would be equivalent of 3 kg of ethanol fuel per kg of dry feedstock, or 1.82 LHV Btu of feedstock per Btu of ethanol fuel.

[167] The optimal size of a biofuels plant is a complicated and location specific calculation. One recent study for several counties in Minnesota showed increasing marginal costs for cellulosic ethanol plants at all sizes greater than 25 million gallons per year. See: Daniel Petrolia, *The Economics of Harvesting and Transporting Corn Stover for Conversion to Fuel Ethanol: A Case Study for Minnesota*, Staff Paper P06-12, Center for Transportation Studies, University of Minnesota (August 2006), p. 35. Available at: http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=1430

[168]USDOE/EIA, *U.S. Fuel Ethanol Plant Report*, November 29, 2011. http://www.eia.gov/petroleum/ethanolcapacity/

[169] Oak Ridge National Laboratory, *Biomass as a Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply* (ORNL, prepared for USDA and DOE, April 2005). http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

[170]U.S. Department of Energy (2011), *U.S. Billion Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R. D. Perlack and B. J. Stokes (Leads), ORNL/TM-2011/224, Oak Ridge National Laboratory, (Oak Ridge, TN. (August 2011). http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf

[171] Only negligible amounts of cellulosic fuels are currently produced, so the efficiency of commercial-scale cellulosic plants cannot be directly observed. DOE estimates yields of 78 gallons ethanol per ton for corn stover. (see: US Department of Energy, *Biomass Multiyear Program Plan* (November 2011), p. D-1. http://www1.eere.energy.gov/biomass/pdfs/mypp_november_2011.pdf. EPA estimated 92 gallons ethanol/ton as the average yield in 2022 for its *Regulatory Impact Analysis* for the Renewable Fuels Standard. (US EPA, *Renewable Fuel Standard (RFS2) Regulatory Impact Analysis*, [EPA-420-R-10-206] (March 26, 2010), p 285. See: http://www.epa.gov/otaq/renewablefuels/420r10006.pdf). Prospective ethanol producer Coskata claims yields of 100 gallons ethanol per ton for its demonstration-scale plant. (See: http://www.coskata.com/process/) Kior claims yields of 66 gallons diesel per ton for its currently-under-construction biomass-to-diesel hybrid technology, which is close to 90 ethanol equivalent gallons per ton http://www.kior.com/content/?s=6&s2=56&p=56&t=Production-Facilities

[172]U.S. Department of Energy (2011), *Billion Ton Update.*

[173] Environmental Protection Agency, *Renewable Fuel Standard (RFS2) Regulatory Impact Analysis*, [EPA-420-R-10-206] (March 26, 2010), p. 281-282. See: http://www.epa.gov/otaq/renewablefuels/420r10006.pdf. Note that EPA expects a smaller scale for cellulosic ethanol plants using municipal solid waste as a feedstock, but does not expect municipal solid waste to be a large contributor to total ethanol volumes.

[174] In their most recent update, DOE specifies 2,000 dry tons of feedstock per day. Assuming 330 stream days/year x 78 gallons/ton feedstock equates to 51.6 million gallons per year. US Department of Energy, *Biomass Multiyear Program Plan* (November 2011), p. 2-53. http://www1.eere.energy.gov/biomass/pdfs/mypp_november_2011.pdf.

[175] Daniel Petrolia, *The Economics of Harvesting and Transporting Corn Stover for Conversion to Fuel Ethanol: A Case Study for Minnesota*, Staff Paper P06-12, Center for Transportation Studies, University of Minnesota (August 2006), p. 35. Available at: http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=1430

[176] Pursuant to EISA, EPA issues an annual rule based on anticipated cellulosic biofuel production in the coming year. Environmental Protection Agency, *Regulation of Fuels and Fuel Additives: 2012 Renewable Fuel Standards: Final rule*, December 22, 2011, p. 7. EPA projects production of 4.8 million gallons from KiOR in 2011. See: http://www.epa.gov/otaq/fuels/renewablefuels/documents/rfs-2012-standards-final-rule.pdf. KiOR indicates that the plant will become operational "in the second half of 2012." KiOR says that future facilities will have a capacity of about 33 million gallons per day. See: http://www.kior.com/content/?s=6&s2=56&p=56&t=Production-Facilities. INEOS describes its plant here: http://www.ineosbio.com/94-Indian_River_BioEnergy_Center.htm

[177] Meng Ni, Dennis Leung, Michael Leung, and K. Sumathy, "An Overview of Hydrogen Production from Biomass," *Fuel Processing Technology*, Volume 87 (2006), pp. 461-472. See: http://scienzechimiche.unipr.it/didattica/att/8a94.1244.file.pdf

[178] Amelia Milbrandt and Margaret Mann, *Hydrogen Resource Assessment: Hydrogen Potential from Coal, Natural Gas, Nuclear, and Hydro Power*, (National Renewable Energy Laboratory, NREL-TP-560/42773, February 2009), p. 5. See: http://www.nrel.gov/docs/fy09osti/42773.pdf

[179]The Japan Atomic Energy Agency is testing this approach with an experimental 30 MW high temperature gas reactor. See: Shusaku Shiozawa, Masuro Ogawa, and Ryutaro Hino, "Future Plan on Environmentally Friendly Hydrogen Production by Nuclear Energy," in: Nuclear Energy Agency, *Nuclear Production of Hydrogen: Third Information Exchange Meeting, Oarai, Japan, 5-7 October 2005*, (Paris: OECD) p. 47.

[180]cf: M. Ruth, M. Laffen, and T. Timbario (2009). *Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios*, (National Renewable Energy Laboratory NREL/TP-6A1-46612), September 2009, p. 194. http://www.nrel.gov/docs/fy10osti/46612.pdf

[181] GREET 2011 indicates 2015 well-to-wheel carbon dioxide emissions of 452 g/mile for a conventional gasoline vehicle, 95 g/mile for an E85 cellulosic ethanol conventional vehicle, and 238 g/mile for a fuel cell vehicle using hydrogen from natural gas with no sequestration. See: http://greet.es.anl.gov/. Hydrogen-from-natural gas is more emissions intensive than conventional gasoline: all of the improvement comes from the improved efficiency of fuel cells vis-à-vis internal combustion engines.

[182] Christopher Yang and Joan Ogden (2007), "Determining the Lowest-Cost Hydrogen Delivery Mode, *International Journal of Hydrogen Energy*, Volume 32 (2007), pp. 268-286. pubs.its.ucdavis.edu/download_pdf.php?id=1162

[183] Yang and Ogden (2007), and Nathan Parker, *Optimizing the Design of Biomass Hydrogen Supply Chains Using Real-World Spatial Distributions: A Case Study Using California Rice Straw*, (Master's Degree Thesis, University of California at Davis, 2007. http://pubs.its.ucdavis.edu/download_pdf.php?id=1072

[184] Ruth et al (2009), p. 194.

[185] Ruth et al (2009), pp. 194 and 220.

[186] Nils Johnson, Chris Yang, and Joan Ogden (2006). *Build-Out Scenarios for Implementing Regional Hydrogen Infrastructure*, (Proceeding of the National Hydrogen Association (NHA) Annual Conference, Long Beach, California, March 2006). See: http://hydrogen.its.ucdavis.edu/research/track2/tr2pr9

[187] Cf. USDOT (2010), *Transportation's Role in Reducing Greenhouse Gas Emissions*, (April 2010), http://www.reconnectingamerica.org/assets/Uploads/2010DOTClimateChangeReportApril2010.pdf and Urban Land Institute, *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emission*s (July 2009). http://www.movingcooler.info/home

[188]USDOT/EPA (2011), "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles," *Federal Register*, Vol. 176, No. 179, 11 September 2011, p. 57106, http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/2011-20740.pdf and DOT/EPA (2010), "Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule," *Federal Register*, Vol. 75, No. 88, 7 May, 2010, p. 25324. http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/CAFE-GHG_MY_2012-2016_Final_Rule_FR.pdf

[189]USDOT/EPA (2011a), "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards: Notice of Proposed Rulemaking," *Federal Register*, Vol. 76, No. 231, 1 December 2011, p. 74854. http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/2017-25_CAFE_NPRM.pdf

[190] National Research Council (2009). *Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and CO2 Emissions -- Special Report 298*. Washington, DC: The National Academies Press, 2009. http://onlinepubs.trb.org/Onlinepubs/sr/sr298.pdf

[191] NRC (2009), p. 181-182.

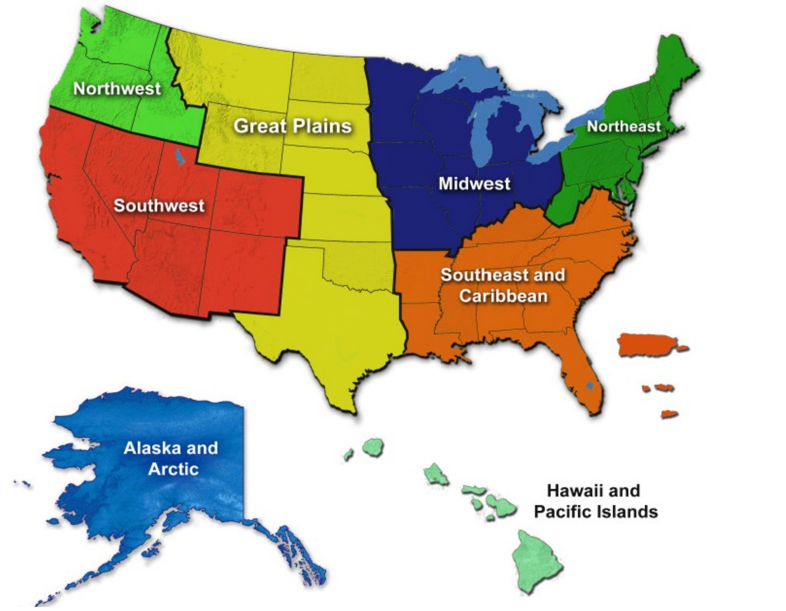
[192] Caroline Rodier (2009), "Review of International Modeling Literature: Transit, Land Use, and Auto Pricing Strategies to Reduce Vehicle Miles Traveled and Greenhouse Gas Emissions," *Transportation Research Record* #2132, (TRB/NAS, 2009). http://trb.metapress.com/content/g885374707j12177/fulltext.pdf

[193] K. Small and K. Van Dender (2007), "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect," *Energy Journal*, Vol. 28, No. 1 (2007), pp. 25-51. With corrections by the authors (2007): http://www.economics.uci.edu/files/economics/docs/workingpapers/2005-06/Small-03.pdf

VI. Climate Impacts on Transportation by Region

A. **Overview**

Figure 28. National Climate Assessment Regions



The previous chapters discussed climate impacts on infrastructure by the nature of the impact. This chapter will explore the various effects by region. The National Climate Assessment divides the United States into eight regions, as shown in Figure 28.

The National Climate Assessment is preparing regional climate projections, based upon the A2 and B1 Scenarios. Pending the completion of these projections, the Federal Highway Administration has prepared recent (2010) guidance on regional climate projections for use by State Transportation Departments.[194] This guidance, however, is not directly based upon a particular IPCC scenario. For maximum compatibility with the ultimate NCA projections, the specific climate projections in this chapter are based upon the 2009 Climate Impacts report.[195]

B. **Alaska**

For Alaska, the future is now. The annual average temperature in Alaska has risen by 3.4° F, while winters have warmed by even more, by 6.3° F.[196] Summer temperatures are expected to increase 3.5-7° F by the 2050s, and 9-12° F by the end of the century under the A2 scenario, 8-13° F under the B1 scenario.[197] Precipitation is expected to increase modestly, but with higher temperatures soil moisture may decline.

Permafrost is a key feature of the Alaskan landscape, which is exactly what it sounds like, soil saturated with frozen water. If the temperature warms enough, there may be a thin “active layer” at the surface that is subject to summer thawing, overlaying a deeper permanently frozen layer. Permafrost has excellent load-bearing characteristics when frozen. Thawed permafrost is mud. If it can be kept cold, permafrost is a suitable base for transportation infrastructure such as roads and airfields. It is often suitable for cross-country travel in winter. Much of the rural transportation infrastructure in Alaska is built on permafrost.

Permafrost is getting warmer. Current warming is already damaging roads and airports in rural Alaska. Road shoulders slump, highway cuts slide, and roadbeds sink. The Alaska Departme of Transportation and Public Facilities reports that the State is spending an extra $10 million per year in repairing permafrost damage now.[198]

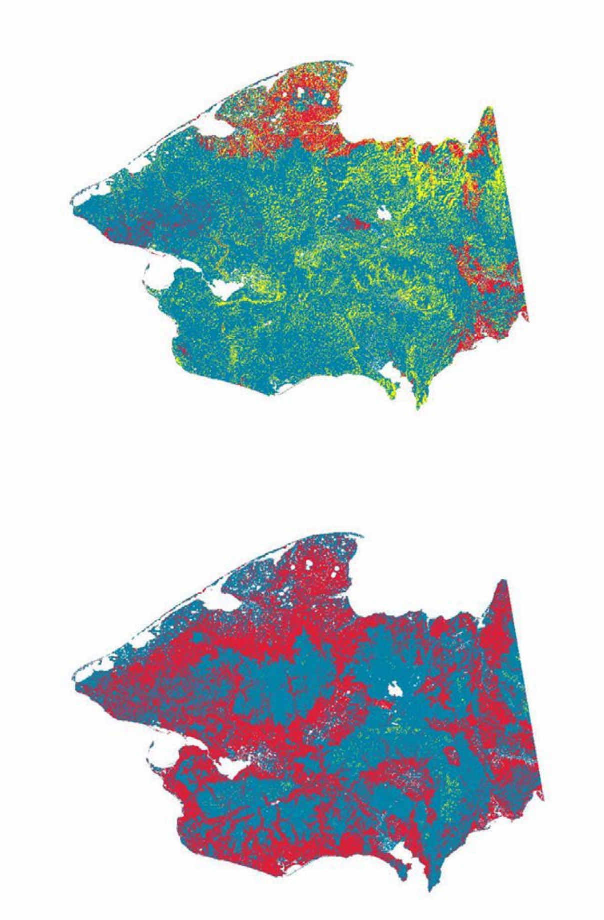
Figure 29 shows a 2007 projection of changes in permafrost in Alaska's Seward Peninsula over the next century.

A study sponsored by the Institute for Economic and Social Research at the University of Alaska inventoried public infrastructure at risk in Alaska under the mid-range IPCC A1b scenario, using results from three different climate models.[199] The transportation infrastructure enumerated by the study included 253 airports, 853 bridges, 131 harbors, 819 miles of railroad track, 4,576 miles of paved road and 5,000 miles of unpaved road.

This study is methodologically interesting, in that it modeled climate change impacts in the form of a Monte Carlo simulation of premature replacement of infrastructure that was subject to probabilistic damage (largely from permafrost thawing) with increasing temperatures. The authors then modeled adaptation in the form of replacement of infrastructure as required with more robust but more expensive designs that were less subject to further damage, yielding an estimate of climate costs with and without adaptation.

Figure 29. Permafrost Distribution on the Seward Peninsula, 2000 vs 2100

(Yellow=Continuous; Blue=Discontinuous; Red=Thawing Permafrost/Permafrost Free)



Source: Hinzman, L., R. Busey, and J. Cassano (2007), as reproduced in: Larsen, Goldsmith, Smith, Wilson, Strzepek, Chinovsky, and Saylor, *Estimating Future Costs for Alaska Public Infrastructure At Risk from Climate Change* (IESR, UAA, June 2007).

In the absence of adaptation, the study estimated the net present value of additional public transportation infrastructure costs (at 2.85 percent discount rate), at $2.3 -$4.3 billion through 2030, and $4.0 - $7.6 billion through 2080, depending on the climate model chosen to represent the A1b scenario in Alaska. With adaptation, savings with a net present value of $0 – $0.6 billion were realized through 2030, and $0.4 - $3.4 billion through 2080. The extra cost of climate change is 9-18 percent of total transportation infrastructure costs without adaptation. With adaption, the cost of climate change is 9-15 percent through 2030 and 9-11 percent through 2080. Savings from adaptation scale with climate damage costs. At the very lowest levels of climate damage, savings from adaptation are negligible, but become very large when climate impacts are large.

Upgrading infrastructure provides the greatest payout when climate change effects are most severe, so benefits are largest under the model with the greatest climate sensitivity, and accrue mostly during the later time periods when climate effects are most severe. It is striking that in this model, extra spending on adaptation not only reduces total cost, but it reduces the sensitivity of costs to increased climate change, so it has a risk reduction as well as a cost-saving effect.

This analysis focused entirely on the infrastructure replacement aspects of climate impacts. Impacts on transportation system performance, either from direct climate impacts or from damage to infrastructure were not included.

In recent years, there has been an increase in storm activity along the Alaskan coast that appears to be correlated with reductions in ice cover, possibly because ice-free waters make available more heat and moisture for storm activity.[200] In addition, climate induced changes in air pressure may move Pacific storm tracks Northward and into Alaska. Increased storminess presents particular safety challenges for general aviation-dependent portions of Alaska, as well as for the operation of marine vessels and motor vehicles, and may present flood risks in some coastal area.

Sea level rise has not received extensive attention in Alaska, though shoreline erosion of coastlines that were formerly icebound, particularly along the Beaufort Sea North of the Bering Strait, has inflicted significant damage on several coastal villages, and is expected wreak further damage. A number of coastal villages are being effectively abandoned and the population relocated. The Southeastern Alaskan coastline is largely high relief, and hence relatively insensitive to sea level rise, and some portions of Alaska are undergoing tectonic uplift. Anchorage, home to about half of Alaska's population, is comfortably above sea level. However, sea level rise can only exacerbate the effects on fragile shorelines.

C. **Northeast**

The Northeast in the NCA schema encompasses New England, New York, New Jersey, Pennsylvania, Delaware, Maryland, West Virginia, and the District of Columbia.

Over the next few decades, average winter temperature is predicted to increase 2.5 to 4° in winter and 1.5 to 3.5° in summer. Precipitation intensity will increase and spring snowmelt will occur earlier in the year, increasing the risk of flooding. The growing season may also lengthen, increasing the viability of certain crops. The track of tropical storms will gradually shift northwards, leading to increased risk of flooding and storm surge.[201]

By the end of the century, under a high emissions scenario, cities that today experience fewer than 5 days above 100° F each summer would average 20 days above 100° F while certain cities, such as Hartford and Philadelphia, would average nearly 30 days over 100° F. Vermont will have a climate similar to Virginia or North Carolina's current climate.[202]

The Northeast is the most heavily urbanized and densely populated of the NCA regions, and its infrastructure is relatively old in comparison with other parts of the United States. Higher temperatures may require extensive re-fitting of rail lines, changes in asphalt mix as roads are resurfaced, and more consideration of cooling in design of structures. In essence, design practices now common in the South will migrate north as temperatures rise.

The effects of precipitation changes are more complex. Over the past twenty years, the Northeast has already experienced significant increases in the amount of precipitation, and a 67 percent increase in intense precipitation.[203] Reduced snowfall and frost will produce multiple benefits for transportation systems: reducing annual snow clearance costs, improved system reliability, reduced vehicle and infrastructure damage from snow clearance operations. On the other hand, increased precipitation falling as rain will tend to reduce transportation system capacity and reliability. Aging infrastructure will be exposed to hydrologic conditions not anticipated by its designers.

Increased intensity of precipitation increases flood risk, which can cause system interruptions, infrastructure damage, or both. Increased urbanization, unless offset by improved storm water management, will tend to increase run-off from a given level of precipitation.

For aviation, intense thunderstorms pose a special risk, sometimes requiring temporary closures of runways or airports, presenting particularly acute system problems in the crowded air space of the Northeast.

Increased intensity and variability of precipitation poses planning problems for system operators, and design problems for infrastructure owners. Highway and airport managers may have to keep the resources on hand to dig out from the occasional large snowstorm, even if the frequency of snowstorms diminishes. Infrastructure designers may have to produce more robust designs to cope with extreme events. The recent experience of the Northeast with Hurricane Irene may be an indicator. Irene made landfall on Long Island as a marginal Category 1 hurricane and caused only incidental damage from wind and storm surge. However, the storm delivered "100-year event" scale rains and "500-year event" stream flows along its western flank, causing extensive flooding, mudslides, destruction of houses, roads, bridges, and rail lines, and more than 40 reported deaths.[204] In Vermont, press reports indicate damage to state roads costs $175-$250 million to repair, and many roads were closed for months.[205] In rebuilding, transportation managers in the Northeast will have to decide whether Irene-scale rains is an once-in-a-lifetime event, or the shape of things to come.

Sea level rise will become especially significant by the end of the century. Currently, sea levels in the Northeast are 0.6 to 0.7 meters lower than the global average, and climate change may cause sea levels to rise more than the global average, which for which the NCA mid-point projection is now 1.4 meters.[206]

Because sea levels are now expected to increase rapidly, regional case and scenario studies on the Gulf Coast, Chesapeake Bay, Boston, and New York City may have to be revised. For example, Kirshen estimates that a 2005 100-year storm surge event would occur every 8-35 years or less in low-lying areas such as Boston or Atlantic City or every 30-70 years in higher coastal areas.[207] However, his data is based upon extrapolating historical sea level rise in local areas. Given that sea level rise seems likely to accelerate, cities such as Boston may face a much higher frequency of extreme storm surge events, perhaps at the order of every 8 years at the very least. As noted in Chapter IV, the Port of New York and Kennedy Airport are particularly important infrastructure assets that are potentially at risk from sea level rise.

Because of natural subsidence, the Chesapeake, which is shared between the NCA Northeast and Southeast regions, is particularly at risk. In the Northeast, the Maryland DOT has conducted a sea-level-rise vulnerability assessment of all State transportation infrastructure. They agency plans to incorporate sea-level-rise considerations into future transportation decision-making and develop plans to relocate sensitive infrastructure where necessary.[208]

The U.S. Department of Transportation's Climate Center also commissioned a set of maps of areas potentially at risk for sea-level rise, based upon USGS 30-meter digital elevation data.[209] The extent of sea-level rise examined in this study is less than currently projected for 2100, but may be useful for considering near-term impacts. These maps are useful for screening and indicative purposes, but should not be used for detailed planning, since the resolution of the source data is relatively low, may be dated and does not include many man-made features.

The probability of hurricanes making landfall may be lowered by rising vertical wind shear, a hurricane-killing condition, from climate change. However, hurricane strength is likely to increase. In addition, tracks of winter storms (nor'easters, not hurricanes) appear to be shifting northward.[210]

Transportation agencies in Northeastern cities have undertaken several significant changes to make their cities more resilient to the threat of extreme events. Openings to the underground system, for example, have been elevated. New York City and Boston have enacted extensive adaptation plans, which highlight the need to integrate adaptation into many aspects of city planning. The New York City plan noted that some New York subway stations were as low as 180 feet below sea level, and that a single intense storm in August 2007 caused a near-systemwide outage on the Municipal Transit Authority system during the morning rush hour.[211] In addition to physical adaptation measures, the authors also note: "The flexibility of transit users to shift from one system to another is an important adaptation mechanism."[212]

A recent study of adaptation in New York (Rosenzweig, 2011) which included a discussion of the economic costs of a 100-year storm in New York City with sea-level rise, was briefly discussed in Chapter IV, as was a study of potential travel delay from flooding in Boston.[213]

The aging infrastructure of the Northeast presents both risks and opportunities with respect to climate change. Pennsylvania, for example, has over 6,000 structurally deficient bridges in the nation, but its 2008-2010 Accelerated Bridge Program has replaced more than 500 bridges per year. Structurally deficient bridges are vulnerable to heat and scour but their gradual replacement gives opportunities for more robust designs and materials.[214] It is not clear, however, whether the Pennsylvania replacement program has considered climate-driven hydrologic changes in its bridge replacement program.

Heat will eventually pose a problem but as a short-term measure, engineers in the Northeast could anticipate higher temperatures by creating higher temperature standards for rails and pavement, potentially matching the 100-degree pavement and rail thresholds found in the Southeast.

Another special feature of the Northeast is the Northeast rail corridor, connecting Washington, Baltimore, Philadelphia, Wilmington, Newark, New York City, and Boston. The Northeast corridor is the most heavily traveled passenger rail corridor in the United States, and is one of the relatively few electrified sections. Electrified rail lines are subject to particular risks, including wind damage and ice and snow damage.[215] The Northeast corridor is used by Amtrak but is also shared by many state and local commuter rail operations. Portions of the corridor run close to the Chesapeake and the Delaware River, and may be at risk for flooding and relative sea level rise. The Northeast corridor competes with commercial air service, but rail and aviation service outages are rarely simultaneous. The existence of competing modes with different risks adds to the reliability of passenger travel along this important route.

D. **Southeast**

The NCA Southeast region includes the middle and Southern Atlantic from Virginia to Florida, and the Gulf Coast as far West as Louisiana, plus the inland states of Kentucky, Tennessee, and Arkansas.

The transportation infrastructure of the Southeast, especially around the Gulf Coast, faces serious risk from the flooding of various rivers, hurricanes, drought, and sea level rise, which is compounded by the economic importance of Southeastern ports in international trade and energy. Since 1970, the average temperature of the Southeast has risen about 2° F. Under a lower emissions scenario, average temperatures are projected to rise about 4.5° F by the 2080s while a higher emissions scenario will result in about 9° F of warming, with most of the increase occurring during the summer. As a result, the number of very hot days is projected to rise at a greater rate than the average temperature.[216]

Average autumn precipitation has increased by 30 percent in the region since 1901. It is unclear what the exact effects of climate change will be on overall precipitation over the next century, although some analyses of South Florida show that spring and summer rainfall is projected to decline there.[217] Though the recent prolonged drought throughout the Southeast is assumed to be a typical climactic event with limited influence from climate change, it is possible that drought events may increase.[218]

Though overall precipitation levels over the next century are unclear, an increase in average sea level of at least 2 feet and the likelihood of increased hurricane intensity and associated storm surge pose significant threats to transportation infrastructure in the region. In the Gulf Coast area alone, an estimated 2,400 miles of major roadway and 246 miles of freight rail lines are at risk of permanent flooding within 50 to 100 years as global warming and land subsidence (sinking) combine to produce an anticipated relative sea-level rise in the range of 4 feet or more.[219]

Sea level rise thus imposes a serious economic cost on the road infrastructure of the Gulf Coast. For example, damage due to long term submersion of roadways in Louisiana was estimated to be $50 million for just 200 miles of state-owned highway. The Louisiana Department of Transportation and Development noted that a total of 1,800 miles of roads were under water for long periods, requiring costly repairs.[220]

The threat of relative sea level rise is complementary to the increasing severity of storms, though it is unclear whether the frequency of storms that make landfall will change. Major storms such as Hurricane Katrina are likely to become more common occurrences. During the storm, barge shipping was halted, as were grain exports from the Lower Mississippi, the nation's largest grain export route. Oil and gas pipelines were shut down by personnel evacuations and loss of electrical power, producing shortages of natural gas and petroleum products. Total recovery costs for the roads, bridges, and utilities as well as debris removal have been estimated at $15 billion to $18 billion.[221] Risks to grain elevators are discussed in Chapter IV.

This region is also home to a substantial portion of the US oil and gas industry, with major offshore drilling platforms, refineries, and pipelines. Roughly two-thirds of all US oil imports are transported through this region. Relative sea-level rise and flooding may disrupt Gulf Coast refineries. Climate risks to oil and gas facilities are discussed in Chapter IV.

According to the Department of the Interior, there are over 3,000 offshore oil platforms in the Gulf of Mexico. In July 2011, there were 679 manned offshore platforms and 62 offshore oil rigs operating in the Gulf.[222] This activity is supported by a complex dedicated infrastructure of ports, yards, specialized construction and repair vessels, and an aviation component including fleets of helicopters and heliports. The ports and yards, including Port Fourchon, Morgan City, Iberia, and Galveston, typically sit at the very edge of the Gulf of Mexico, and are vulnerable to hurricanes, storm surge, and relative sea level rise.

Among the potential second order effects: higher temperatures may also increase refrigeration needs for goods during transport, particularly, raising transportation costs.[223] These factors, in addition to sea level rise and increasing temperatures, may decrease the competitiveness of Southern ports.

Transportation agencies in the Southeast are engaging in several studies and measures to study and adapt to climate change. The comprehensive DOT Gulf Coast study is being conducted in three stages. Phase 1 looked at the vulnerabilities and impacts of climate change on the region as a whole and was completed in 2008. Phase 2, which is scheduled to be completed in 2013, focuses on the Mobile, Alabama region and aims to understand the most vulnerable transportation components as well as the most promising adaptation measures at a local scale.[224]

Florida adopted the extensive Energy and Climate Change Action Plan in 2008 and the Strategic Intermodal System (SIS) in 2010, which together call for an evaluation of areas most vulnerable to sea level rise as well as retrofitting of bridges and highways to withstand future events.[225]

E. **Midwest**

The NCA Midwest region encompasses Michigan, Ohio, Illinois, Indiana, Missouri, Wisconsin, Iowa, and Minnesota.

Flooding is an especially prominent threat to Midwestern and Great Lakes transportation infrastructure. Higher temperatures and heat waves may cause failures in rails, pavement, and transit. Finally, the reliability of trade occurring along the Mississippi River is a developing concern.

Heat waves such as the Chicago Heat Wave of 1995, which resulted in over 700 deaths, are projected to occur once every three years by the end of century under the lower emissions scenario.[226] Under the higher emission scenario, they are projected to occur three times a year.[227] In addition to the number of fatalities from the extreme temperatures, the heat wave also caused miles of rail and pavement to buckle, extreme discomfort in underground systems and outdoor transit stops, and mechanical failure in transportation-related machinery such as engines.

Extreme temperatures may also become increasingly common. The 2010 and 2011 heat waves through the Northeast and Midwest led to several traffic backups because of buckling pavement. For example, in 2011, extreme heat caused pavement to buckle on I-75 near Dayton, Ohio, leading to an hours-long traffic jam. At the same time, Union Pacific Railroad had to inspect railroads twice a day, and all trains were slowed down to speeds of 10 to 20 mph.[228]

The Midwest and Great Plains regions have experienced three record-breaking floods in the past 20 years: the Great Flood of 1993, the June 2008 Midwest Flood, and the summer 2011 Missouri River-Mississippi River floods. In the 1993 floods, catastrophic flooding occurred along 500 miles of the Mississippi and Missouri River systems, affecting one quarter of all US freight. In the June 2008 floods, dozens of levees were breached or overtopped in Iowa, Illinois, and Missouri, flooding huge areas. Long sections of road and rail were impassable.[229]

Most recently, the summer 2011 Missouri-Mississippi River floods have been considered to be on par with the Great Flood of 1993, causing $2 billion in levee damage alone according to the U.S Army Corps of Engineers.[230] The total costs will likely be two or three times higher after incorporating transportation losses, real estate damage and more. The flooding closed traffic bridges, making it impossible to cross the river for 200 miles - 100 miles between Sioux City and Omaha and another 100 miles between Plattsmouth, Nebraska and St. Joseph, Missouri.

The 2011 floods were caused by extremely heavy rainfall in conjunction with an estimated 212 percent of normal snowpack in the Rocky Mountains of Montana and Wyoming from an unusually cool and wet spring. The collection of these climate-related factors initiated flooding throughout a three month long period. Flooding downstream was exacerbated by the need to regulate the release of water in reservoirs and dams upstream, which were overflowing.
Such flooding is projected to occur with greater frequency, especially during the late spring and early summer months. Rights-of-way are valuable and difficult to shift. Consequently, it will often be best to defend, rather than attempt to move, threatened infrastructure. However, analyses of areas most likely to flood will be helpful in the allocation of resources for long range transportation plans as well as levee construction.

Finally, long-term and gradual changes will affect regional freight and rail transportation in two major ways. Great Lakes and Mississippi river water levels are likely to fall. Lower lake levels reduce "draft" or the distance between the water line and the bottom of a ship, which thus reduces a ship's carrying capacity. Great Lakes water levels are discussed in Chapter IV.

Potential shifts in agricultural product flows are also discussed in Chapter IV. One study indicates that as corn and soya bean cultivation moves northward, agricultural shipments will shift onto rail moving onto the Pacific Northwest, and onto Great Lakes shipping moving East.

F. **Great Plains**

The NCA "Great Plains" region covers a strip of the central United States running from Montana and North Dakota on the Canadian border, to Texas on the Gulf Coast.

This region is difficult to examine in isolation in the context of transportation impacts. Texas' transportation impacts are primarily shared with the Gulf Coast, part of the Southeast region. On the other hand, the balance of the region primarily shares climate impacts with the Midwest, but excluding the Mississippi River. However, shipping on the Mississippi remains of considerable importance.

The Great Plains are transited by major East-West road and rail links. The immense volumes of coal shipped from the Powder River Basin in North Dakota flow by rail through the Great Plains, as discussed in Chapter IV.

Agricultural products, discussed in Chapter IV, flow out of the Northern plains by barge along the Mississippi, but also by North-South rail links. Both the barge and rail routes are potentially vulnerable to floods and low water on the Mississippi and its tributaries.

Texas, on the other hand, shares the risks of relative sea level rise to grain ports and the petroleum industry discussed in Chapters IV and V with the rest of the Gulf Coast.

G. **Southwest**

The National Climate Assessment includes California, Nevada, Utah, Colorado, Arizona, and New Mexico within the Southwest Region.

This region includes most of the Colorado River basin, the Southern Rockies, and the Sierra Nevada. Much of the Southwest region is dependent for water and electricity on a network of snowmelt-fed dams. Possible climate-induced changes in the future performance of these systems is probably the largest potential impact in this region, and second-order effects on agriculture, energy, and settlement patterns may affect transportation systems. While energy and water-related problems will be especially prominent in the Southwest, the transportation sector is also vulnerable to other climate impacts, especially increased temperatures and increased severity of wildfire.

The Southwest's already dry climate will become even drier by the end of the century, thus exacerbating water scarcity in the region. Note, however, that the exact boundary between a broadly wetter Northwest and a broadly drier Southwest is uncertain. Wetter conditions could extend into Northern California and the Sierra Nevada. Given the economic importance of precipitation the Sierra to California, this uncertainty presents a particular planning headache.

Compared to a 1970 baseline, temperature will rise about 3 to 5° by mid-century under a low-emissions scenario and 3.5 to 5.5° under a high-emissions scenario. By the end of century, a low-emissions scenario will cause a 4 to 6 degree rise while high emissions will lead to a 7 to 10 degree increase, thus causing serious desiccation in many areas around the Southwest.

Heat damage may pose engineering challenges by mid-century. Temperatures in the Southwest are already the highest in the nation, and the continued increase in temperatures due to climate change will result in unprecedented temperatures. Currently, infrastructure in the inland Southwest is built to withstand extreme temperatures to over 110° F, but higher temperatures may cause pavement to buckle.

Some portions of the Southwest are especially prone to wildfires. For example, a warming of 1.8° F would produce 200 to 400 percent increases in median area burned. The Texas wildfires of September 2011, for example, were the result of the confluence of drought, high temperatures, and rainless winds from a nearby tropical storm. Ultimately, the Texas wildfires caused $152 million in damage to agriculture.[231] This sum was only a small fraction of the total damages from the extended drought in Texas, which have resulted $5.2 billion in crop and livestock losses over the course of the year. The wildfire was caused in large part by the driest, hottest summer on record since 1895.[232]

Where precipitation forecasts are mixed or varied for many regions in the United States, drought events are very likely to increase the Southwest. By the end of the century, spring precipitation will likely decrease by 15 percent in many areas of the Southwest and more than 30 percent by the end of century. No consensus currently exists on the summer monsoon, but overall the decrease in spring precipitation is likely to be more than enough to offset summer rains.

The combination of altered hydrology and increases in temperatures means that it may become increasingly costly or even unviable to raise certain livestock or crops in the Southwest. Cropped acreage in Texas, for example, is predicted to decline by about 20 percent by the end of the century.

Studies of sea level rise along the Pacific coastline are underway. The State of California, in its guidance document for its agencies, says that "recent studies of regional mean sea level variability indicate that over long timeframes, sea level along the California coast tend to compare well with the global trends."[233] As a first approximation, the current NCA guidance of 1.4 meters as the mid-point of sea-level rise for 2100 is likely to be applicable to the California coast. The State of California's current high case is 55 inches (1.397 m).

In general, the coastline is rocky and relatively high relief, which makes it relatively resistant to erosion and sea level rise. Unfortunately, the exceptions include much of the shoreline of San Francisco Bay and parts of Orange County.[234] According to a study prepared for the California Energy Commission, the population at risk (based on current population) from a 1.4 meter sea level rise combined with a 100-year flood is 480,000 people.[235] Using the same methods, the estimated population currently at risk from a 100-year flood with no sea level rise would be 140,000 people, and 160,000 people for a 0.5 meter sea-level rise. The areas potentially at risk include important transportation infrastructure, including freeways, sections of the BART heavy rail system, two major airports, and the Ports of Oakland and Long Beach.

The Ports of Long Beach and Los Angeles are key transportation links between the United States and the Pacific Basin. In 2010, Long Beach handled more container traffic than any other port in the United States, and the two ports jointly handled almost 30 percent of the national total.[236] Oakland is an important alternative to Long Beach and Los Angeles, handling about 5 percent of national container shipments.[237] Interruptions to shipments in either port, either because of storm events, sea level rise, or closure of landside connections, would materially affect U.S. commerce. A simultaneous interruption to service at both ports would present a significant logistical problem, particularly given that the only other major container ports on the Pacific Coast are on Puget Sound, in Washington State.

Major North-South and East-West interstate freeways, railroads, and pipelines pass through the San Joaquin Valley, providing service to the coastal cities. The San Joaquin and Sacramento Rivers drain into San Francisco Bay, with much of their routes lined by levees protecting reclaimed land.[238] Transportation routes in the San Joaquin Valley are also potentially subject to flood events or interactions between higher sea levels in San Francisco Bay and extreme storm events.

H. **Northwest**

The Northwest region in the National Climate Assessment encompasses Washington, Oregon, and Idaho. The Northwest, like the Southwest, is dependent for water and electricity on a network of dams that capture winter precipitation. Possible climate-induced changes in the future performance of these systems may be an important impact in this region, and second order consequences for agricultural and settlement patterns may affect transportation systems. Regional-scale climate projections suggest and earlier studies suggest that the Northwest will generally be warmer and wetter over the 2040-2070 period, while the Southwest will be warmer and dryer. However, the exact border between the climactic regions varies by model, scenario and time period. The principal long-term impacts on transportation systems may be second-order impacts of changes in agricultural production, settlement patterns stemming from climate impacts on water systems.[239]

In areas where it snows along the Northwest, stream flow may increase in winter and early spring while it may decrease in late spring, summer, and fall. Earlier runoff, for example, was a partial cause to the 2011 summer floods. Earlier melt in the region will likely result in increased risk of flooding in the spring. Further, as in the summer 2011 floods, the combination of earlier snowmelt and increased precipitation – both consequences of climate change – across the continental interior will likely result in increased flooding.

A recent study of climate impacts in Washington State, largely based upon the IPCC A1b scenario (a relatively high emissions scenario), suggests that some watersheds (typically mid-elevation) may shift from precipitation falling as snow to precipitation falling as rain, leading to higher peak flows and a shift from a summer to a winter peak flow.[240] The study suggests the Yakima River watershed as an example of an area that is likely to transition from snow-dominated to rain-dominated under climate change. The study found only minor differences in regional projections between the A1b and the B1 scenarios through the 2050s.

The climate modeling on which this study was based does not suggest a notable increase in extreme events, other than in the Puget Sound region, which is a major population center.

For infrastructure operators, the key issue will be coping with changing precipitation patterns. The Washington State Department of Transportation is conducting a risk assessment of its existing facilities (with funding from USDOT), and the Oregon Department of Transportation is reviewing the risks to its most critical bridges.

There has been a recent integrated study of flooding impacts on urban transportation, focusing on two key watershed areas in the Portland, Oregon, metropolitan area.[241] The study examined four cases: one using the IPCC A1b scenario, and three different downscaled climate models under the IPCC B1 scenario. In 2030-2059, three of the four cases showed significant increases in flood frequency, with the largest increases for the higher emissions A1b scenario. The projected floods were used to close affected bridges in a transportation network, forcing model travelers to route around the closed bridges. As discussed in Chapter IV, the study found negligible (less than 1 percent increases in vehicle miles traveled) but 4 percent and 10 percent increases in vehicle hours delayed under flood conditions. This study did not attempt to calculate economic costs of delay, but if they had done so, the cost would have been small. The basic finding was that drivers in the model could route around the affected bridges, at some cost in additional congestion.

There are several important freight rail links connecting British Columbia with the West Coast, and Pacific ports with the Midwest, including an important North-South rail line running along the shore of Puget Sound.

Current studies of sea-level rise along the Northwest Coast are not yet complete. Older studies indicate that the Washington State coastline is experiencing varying degrees of tectonic uplift, partially offsetting rising sea levels.[242] The Climate Impacts Group, taking uplift and regional factors into consideration, described a range of 0-128 cm rise for Puget Sound in 2100, based on a global sea level rise of 18-93 cm.[243] Given that a recent estimate of global sea-level rise for 2100 is 1.4 meters (4.6 feet), the implication is an updated estimate for Puget Sound would probably be somewhat higher. Generally speaking, the Northwest coastline is relatively high relief, and lacks the deltas and low-lying coastlines of the Gulf and Atlantic Coasts. However, there are specific locations in Puget Sound that appear to be vulnerable. A set of hazard maps, prepared by the Pacific Institute, suggest that elevations at both ports are mostly 10 feet or more above sea level, perhaps sufficient to protect them from most sea-level impacts, though their landside connections may also be at risk.[244]

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[200] USGCRP (2009), p. 143.

[201] USGCRP (2009), p. 107.

[202] USGCRP (2009), p. 107.

[203] USGCRP (2009), pp. 30 and 32.

[204] Complete estimates of Irene's costs are not yet available. An early estimate of the private insurance loss form Irene was $4.3 billion. (See: "Hurricane Irene Insured Loss Estimate Rises to $4.3 billion," *Reuters*, November 28, 2011). http://www.claimsjournal.com/news/national/2011/11/28/195716.htm Total losses will be considerably larger than private insured losses. The death toll is drawn early press reports, such as: N.R. Kleinfeld, "Brave, Foolhardy, and Just Unlucky: The Lives Lost in a Storm's Watery Fury," *New York Times*, 30 August 2011. http://www.nytimes.com/2011/08/31/nyregion/brave-foolhardy-and-just-unlucky-the-lives-lost-in-hurricane-irene.html?pagewanted=all

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